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Advanced Research Sensors and Controls Project Portfolio

Advanced Research

To support coal and power systems development, NETL's Advanced Research Program conducts a range of pre-competitive research focused on breakthroughs in materials and processes, coal utilization science, sensors and controls, and computational energy science—opening new avenues to gains in power plant efficiency, reliability, and environmental quality. NETL also sponsors cooperative educational initiatives in University Coal Research, Historically Black Colleges and Universities, and Other Minority Institutions.

U.S. DEPARTMENT OF ENERGY

NATIONAL ENERGY TECHNOLOGY LABORATORY

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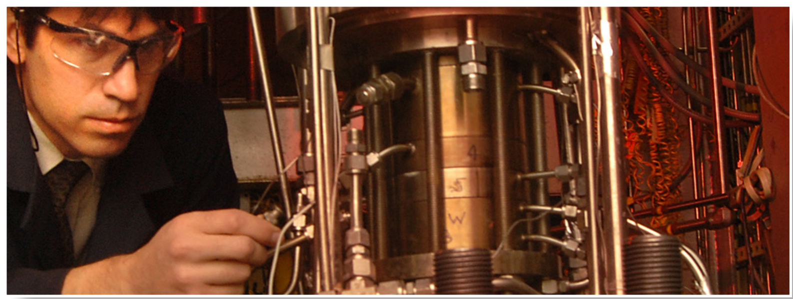
Introduction

Sensors and Controls Program

Novel Sensors and Advanced Process Control are key enabling technologies for future high efficiency, near zero emission power systems. The Advanced Research (AR) Program of the United States Department of Energy (DOE) National Energy Technology Laboratory (NETL) is leading the effort to develop sensing and control technologies and methods to achieve seamlessly integrated, automated, optimized, and intelligent power systems. The performance of advanced power systems is limited by the lack of low-cost sensors capable of withstanding high temperature and pressure conditions and adaptive system controls that can manage inherent complexities of the advanced power systems. Harsh environments are created in new systems to achieve high efficiency with low emissions. In addition, these systems are complex, with operational constraints and system integration challenges that push the limits of traditional process controls. As research and development (R&D) enhances the understanding of these evolving advanced power systems, robust sensing approaches, using durable materials and highly automated process controls, are needed to optimize their operation and performance. New sensors designs will be subject to requirements of packaging for survivability, accuracy, low power consumption, portability, connectivity, and ease of manufacture, installation and use.



The Sensors and Controls Program research projects are categorized into several technology areas. These areas include optical sensing, microsensors, advanced process control, wireless communications, energy harvesting devices, and imaging systems. The optical sensing area covers projects researching novel approaches and materials for monitoring temperature and gas species. The microsensors area includes projects that push current limits of manufacturing sensors for high-temperature and high-pressure environments in smaller and more robust packages. The advanced process control area covers projects focused on computationally based process control of core power systems. The wireless communications and energy harvesting projects fill the need for dense networking of sensors in existing power plants with minimal cost and maintenance impact on installations. Projects from these technology areas are funded by the programs areas listed below.

Coal Utilization Science

The Coal Utilization Science (CUS) Program sponsors R&D in fundamental science and technology areas that have the potential to significantly improve the efficiency, reliability, and environmental performance of advanced power generation systems that use coal, the nation's most abundant fossil fuel resource. The challenge is for these systems to produce power in an efficient and environmentally benign manner while remaining cost effective for power providers as well as consumers. Current research within the CUS Program targets the development of critical and enabling technologies that contribute to the design and operation of advanced near-zero emission power and fuel systems. These systems include the demonstration of multiple commercial-scale Integrated Gasification Combined Cycle (IGCC) or other clean coal power plants with cutting-edge carbon capture and storage (CCS) technology. CUS Program participants include businesses, universities, and other national laboratories.

Historically Black Colleges and Universities (and Other Minority Institutions)

The Historically Black Colleges and Universities (and Other Minority Institutions) (HBCU/OMI) program provides a mechanism for fostering cooperative research into fundamental and advanced concepts related to the science of fossil energy resources among participating academic institutions, industry participants, and Federal agencies. Since its inception in 1984, the program has emphasized improving the energy and environmental capabilities of advanced coal, oil, gas, and environmental technology concepts. The program provides students and faculty hands-on experience in developing technologies to promote the efficient and environmentally safe use of coal, oil, and natural gas. Minority participation helps produce the next generation of scientists and engineers with diverse backgrounds, helping ensure a future supply of technically competent U.S. managers, scientists, engineers, and technicians from previously under-utilized populations.

University Coal Research

The University Coal Research (UCR) Program provides grants to U.S. universities to support fundamental research that cuts across NETL's research focus areas and improves fossil energy technologies. Its primary purpose is to improve the fundamental scientific and technical understanding of the chemical and physical processes involved in conversion and utilization of coal. Since the program's inception by Congressional direction in 1980, more than $100 million has been provided and more than 1,700 students have acquired invaluable experience in understanding the science and technology of coal. Due to the support of UCR research grants, industry now uses new developments in technology and knowledge.

Small Business Innovative Research

Small Business Innovative Research (SBIR) is a highly competitive program that encourages small businesses to explore technological potential and provides the incentive to profit from commercialization. By including qualified small businesses in the nation's R&D arena, high-tech innovation is stimulated and the United States gains entrepreneurial spirit to meet specific research and development needs. SBIR targets the entrepreneurial sector because that is where most innovation and innovators thrive. By reserving a specific percentage of Federal R&D funds for small business, SBIR protects the small business and enables competition on the same level as larger businesses. SBIR funds the critical startup and development stages and it encourages the commercialization of the technology, product, or service, which, in turn, stimulates the U.S. economy. Since enacted in 1982, as part of the Small Business Innovation Development Act, SBIR has helped thousands of small businesses to compete for Federal research and development awards. These contributions have enhanced the nation's defense, protected the environment, advanced health care, and improved our ability to manage information and manipulate data.

Technology Areas

Optical Sensing

Optical sensing involves a light source, an optical waveguide, a sensing element or transducer, and a detector. The transducer modulates some parameter of the light traveling inside the waveguide (e.g., intensity, wavelength, polarization, or phase) and the system measures the changes in the signal received at the detector. Most but not all projects supported by AR use an optical fiber as the waveguide. The use of optical fibers has made a significant impact on sensing technology in harsh environments, because they are more sensitive to the parameters being measured and are ideal for applications that require high-temperature and pressure measurements. Under the AR program at NETL, work is being done to solve challenges in the design, fabrication, integration, and packaging of sensing technologies in harsh environments.

Areas of research include ultra high temperature measurement, distributed and multiplexed sensing on single optical fibers, modifying optical materials to achieve better performance of the waveguides, and gas sensing through the use of optical materials and coatings on optical fibers. For example, coatings on the optical waveguide (fiber) can cause a chemistry-derived refractive index change in proportion to the concentration of a gas and the resulting change in the wavelength of the transmitted light can be measured. These coatings can be metal oxide or ceramic (e.g., silica) materials; nanofilm coatings appear to have high sensitivity.

Microsensors

Sensors are increasingly being miniaturized to allow for use in new applications, where space limitations do not allow larger packaging. These microsensors must be accurate and robust, as well as able to withstand high temperature (i.e., 1000 °C). It may be advantageous for the sensor to be passive (i.e., requires no power supply) and operate wirelessly on low power. For instance, radio frequency identification (RFID) is usually passive, reflecting an interrogative signal with a signature bearing the desired information.

Miniaturization also allows placement of sensors in novel locations such as on gas turbine blades, where stringent dynamic requirements are met. In some cases, it also possible to merge the microsensor into embedded sensors and become an integral part of an existing component. In other applications, increasingly popular nanostructures (e.g., nanowires) can be used in microsensors and in the creation of nanosensors.

Harsh environment applications all require that heat resistant materials such as silicon carbide (SiC) or metal oxides are used for substrates, coatings, and thin films. Sensing technologies continue to improve based on advances in material technology.

Advanced Process Control

Control of temperature, pressure, and chemical species is essential for powerplant processes. A 1% absolute change in both heat rate and plant availability provides multimillion-dollar benefits to a 500 megawatt (MW) plant. Since over half of the domestic power supply is provided by large fossil fuel plants, even incremental improvements are worthwhile pursuits. A control algorithm is used to decide how to vary inputs (such as coal feed rate) over time to maintain outputs within a desirable range. Many control algorithms used today are based on sound mathematical relationships that have been utilized since the mid 20th century. As plants become more complex and computational capabilities explode, the opportunities to enable optimized plant operation using emerging technology are both unique and timely. Research and development opportunities include those that improve the core control process of existing and advanced power system as well as to investigate novel control architectures that fully invoke the capabilities of networked sensors, distributed intelligence, and real-time model-based optimization. Process controls can be made up of mathematical relationships, autonomous decision making, model-based (e.g., model predictive) control, or model-free (e.g., model-free adaptive) control. More novel pursuits in this area include self organizing sensor networks, autonomous subsystems, and distributing intelligence within a system or series of systems. Distributed decision making implies more sophisticated algorithms processed on sensor boards or near the electronics used for operating actuation equipment (i.e., valves). In very large power systems, insights from complex system theory may apply. One example is stigmergy, a form of self-organization in which cues placed in the environment affect subsequent actions, leading to complex structures developed without explicit planning or control. Such biologically inspired computational intelligence challenges conventional control architectures for distributed control (which are linear and based on minimization of error and set points).

Computational Modeling for Advanced Sensing

Improvements are sought in all aspects of modeling from algorithms to software engineering. The motivation for better control algorithms is the benefit achieved by even a 1% absolute increase in power plant efficiency. For instance, research is being done on algorithm development for sensor placement. Optimal sensor placement is essential for collecting the right information at the right time to support decision making.

Modeling efforts stem from the motivation to reduce costs and time delays resulting from the use of expensive lab set-ups in research and physical prototypes in the design and engineering phase of projects. To this end, prime mover simulations are done in a standardized software environment called CAPE-OPEN. As an example of a combined scientific and software engineering effort, Aspen Dynamics™ (Aspen Technology, Inc.) is used to create equivalent reactor networks as reduced order models in computational fluid dynamics (CFD) simulation. The use of reduced order models allows a significant speed up in the time to simulate a system including the development work for sensor placement and sensor performance.

Sensor, Wireless Communications, Energy Harvesting Integration

Power plants typically are centrally controlled, with information flowing from points within the plant to the control station via wires. The overarching goal is to reliably transmit information without costly and maintenance-intensive hard-wired installations by using wireless devices, which communicate via radio-frequency (RF) signals. The use of wireless technology can minimize the cost of adopting new sensor devices in existing power plants by reducing installation costs.

Wireless networks can be designed to support the needs of the system and the control and communication architectures. Various topologies are being pursued to support wireless communication such as star (radial) topology and mesh topology. The needs and approach for wireless communication impact the sensor design, power requirements, and utilization of the data/information.

Another goal of wireless development includes methods to obtain information from a harsh environment and send it out to an ambient environment which can then be routed by commercial technology. This effort addresses entirely different challenges in trying to extract meaningful and accurate information.

Alongside wireless signal transmission, another interest to support the adoption of new sensor technology is self powering sensor devices. Self-powered devices avoid the expense and effort associated with power supply, either wired to a power main or provided by batteries requiring periodic replacement. In some cases the cost associated with installing power to the device and wiring the signal back to the centralized location can be cost prohibitive relative to the value the sensor may provide.

Harvesting waste energy to self-power devices could simplify device installation and maintenance. Harvesting power requires a nearby power source and in a large MW fossil fuel plant, the sources of heat and vibration are numerous. Near term applications of harvested energy are to power sensors and wireless communications that monitor the condition of the plant, thus enabling plant operators to improve reliability and performance at a much reduced cost relative to running wiring throughout the plant.

The relevant energy sources for self-powered sensors in industrial applications are vibrational, thermal, and radio-frequency (RF) energy. Vibrational energy can be harvested via piezoelectric, electrostatic, magnetostrictive, and electromagnetic induction. Thermal gradients can yield energy via the thermoelectric (Seebeck) effect. RF harvesting can be used if the wireless sensor is near an RF source such as an alternating current (AC) line.

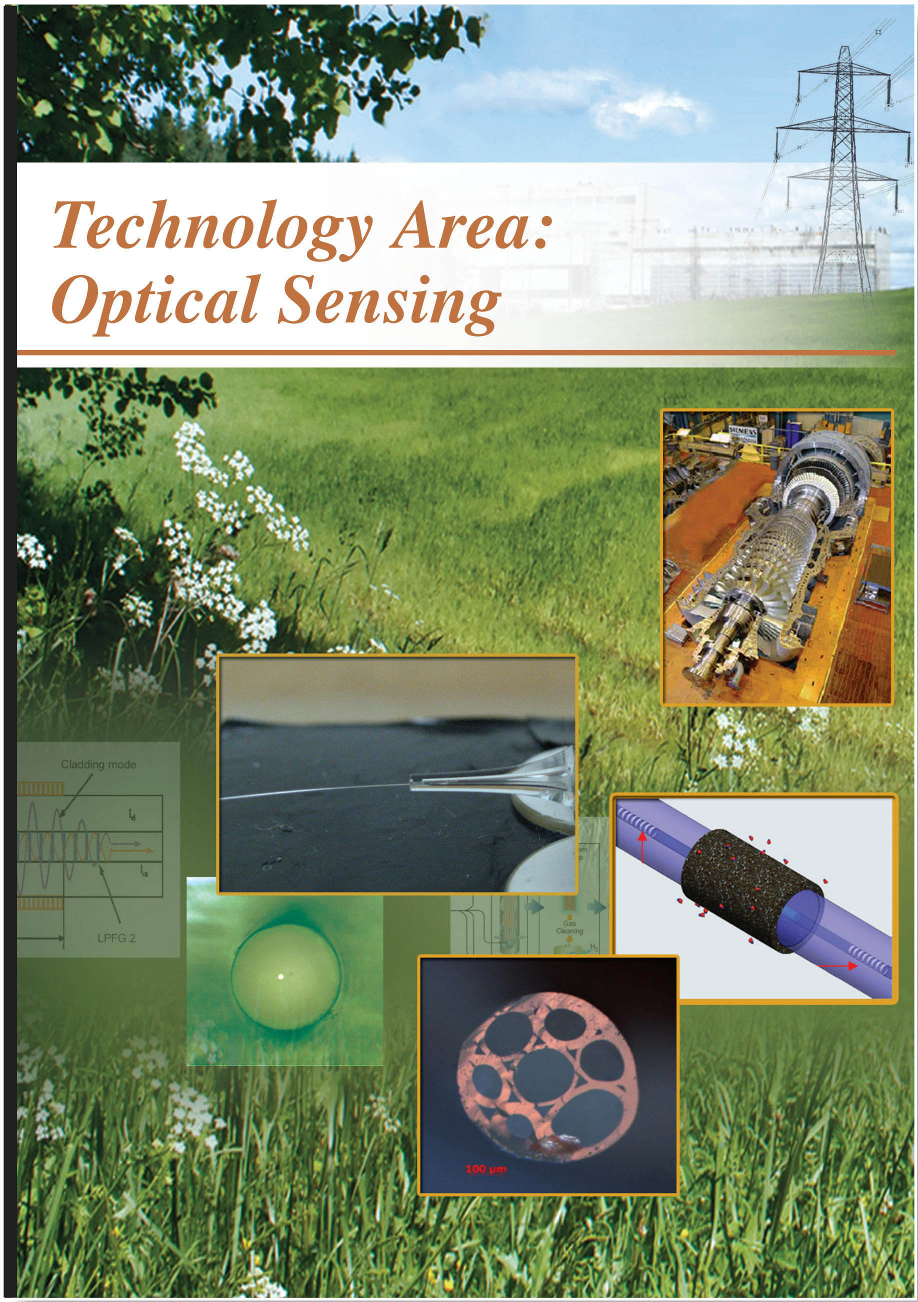
The difficulty of maintaining a nearly 100% reliable self-powered sensor, while harvesting energy only from the environment, implies hybrid approaches. For instance, a backup thin-film battery can be used to provide power when environmental conditions are unfavorable for maintaining the power output, and supercapacitors can be used to handle sharp variations in power draw.

Successful system integration will enable sensors to communicate wirelessly while using harvested energy for self-powering. There are numerous applications for gathering key information in power plants with minimal cost or impact to operations.

Imaging

Images are created when sensors are able to gather and save information about an extended object. High resolution images can be obtained by scanning or sectioning methods. The information received does not need to be optical, but can be based on electrical, magnetic, or other physical properties of the sampling volume. Tomography, in particular, uses a scanning penetrating wave, and conventionally builds three-dimensional reconstructions from a series of two-dimensional scans.

Research and development in this area seeks to enhance visualization capability. In addition, imaging will further support efforts in advanced computing and control through spatial representations of a component or system.


Technology Area:
Optical Sensing
Cladding mode
LPFG 2
100 µm

Development of Metal-Oxide Nanostructure-Based Optical Sensors for Fossil Fuel Derived Gas Measurement at High Temperature

Performer: University of Pittsburgh

Date: 07/30/2010 – 08/31/2013

Cost: $298,395

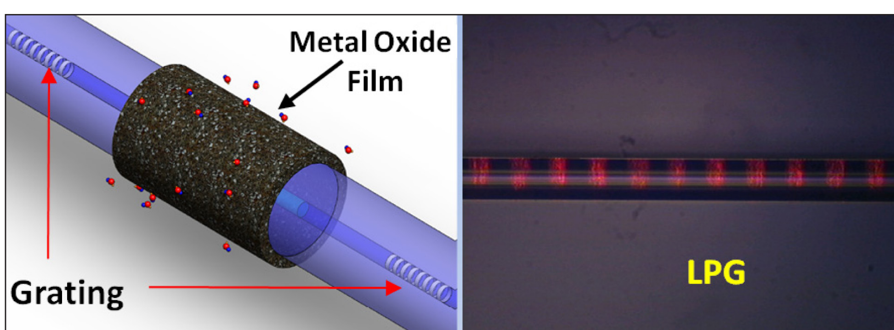
Technology Area: Optical Sensing

Program Area: University Coal Research

Real-time gas composition analysis has multiple critical applications for the energy industry. The precise knowledge of fuel gas composition and its key post combustion derivatives play important roles in improving energy production efficiency and reducing pollution. The goal of this project is to perform nano-engineering to produce functional metal-oxide sensing materials and integrate them with high-temperature optical sensor platforms for real-time fossil-fuel-gas composition analysis.

The objectives of this project are twofold; the first task focuses on the design, fabrication, and three-dimensional (3-D) testing of macro-porous photonic crystals using functional metal oxides. Porous metal-oxide 3-D photonic crystals will be fabricated using a holographic lithography. The surface-chemistry-derived refractive index change or spectroscopic changes will be enhanced by 3-D optical confinement and the large surface area of the porous structure, which can be readily measured remotely through transmission and reflection spectroscopy. To perform multi-species fuel-gas composition analysis, metal-oxide nanostructures can be integrated with high-temperature stable fiber grating devices fabricated by femtosecond ultrafast lasers. The surface chemical-induced refractive index change or structural change can then be measured by the high-temperature stable in-fiber grating sensors. The coating technique can also be developed to synthesize functional metal-oxide films on the inner wall of hollow-core optical fibers. The surface adsorption of fuel gas can then be measured using either Raman spectroscopy or photoluminescent spectroscopy enhanced by the hollow waveguide. The application of hollow-core optical fiber as both the sample gas cell and signal optical collection components can dramatically amplify the sensing signal, leading to orders-of-magnitude enhancements of the signal.

The expected outcome is high-sensitivity optical sensors that can rapidly measure a wide array of fossil-fuel gas species in real time for automatic control of large combustors and fuel cells. The precise and real-time knowledge of fuel gas composition and its key post combustion derivatives will provide data to allow engineers to increase efficiency and lower emissions in energy production from fossil fuels.



Conceptual drawing of coated fiber Bragg grating and photo of Long Period gratings (LPG) on fiber. Figure and photo provided courtesy of University of Pittsburgh.

Development of Nanocrystalline-Doped Ceramic Enabled Fiber Sensors for High-Temperature *in situ* Monitoring of Fossil Fuel Gases

Performer: New Mexico Institute of Mining and Technology, Missouri University of Science and Technology, and University of Cincinnati

Date: 6/21/2005 - 06/30/2011

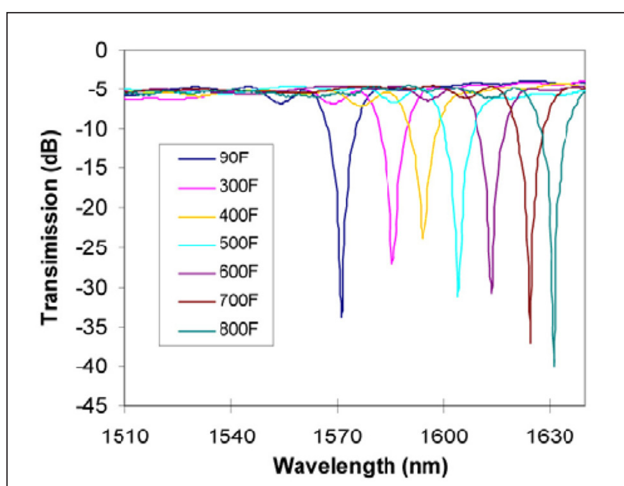
Cost: $1,064,621

Technology Area: Optical Sensing

Program Area: Coal Utilization Science

Reliable and robust sensors are essential to the development of high-efficiency, clean energy technologies such as low-emission power systems that use coal or other fossil fuels. The specific need being addressed by this project is for a new type of sensor suitable for in situ and fast gas monitoring in advanced fossil-energy systems. This sensor will be formed by coating silica-based optical fibers with nanocrystalline-doped ceramic materials. The nanocrystalline structures not only allow formation of functional dense films under temperatures tolerable to the fiber (<750 °C), but also make the films more chemically sensitive than traditional materials in bulk form.

The goal of this project is to develop sensors for high-temperature in situ monitoring of gases found in synthesis gas (syngas) derived from coal. The specific technical objectives of this research include identifying sensor materials with the chemical, structural, and optical properties needed to detect coal-derived syngas; synthesizing nanocrystalline ceramic films and protective silicalite layers on structured optical fibers; designing and fabricating structured fiber devices for enhanced sensor performance; and testing the developed sensors in simulated high-temperature and high-pressure syngas environments. The sensors being developed in this project will help produce affordable and clean energy from coal and other fossil fuels in an effort to secure a sustainable energy economy. Specifically, this device is expected to fill a need for a low-cost, reliable, miniaturized gas sensor that will be capable of fast, accurate, in situ monitoring of gas composition in flue or hot gas streams in the harsh environments characteristic of advanced power generation systems. These new types of sensors are expected to be useful in many critical areas including emissions control, environmental pollutant monitoring, food and water quality assurance, biological and medical analysis, and detection of explosives.



Thermal long-period fiber grating (TLPFG) transmission spectrum at various temperatures (fabricated by CO_2 laser irradiations). Figure provided courtesy of Missouri University of Science and Technology.

Development of Novel Ceramic Nano-Film Integrated Optical Sensors for Rapid Detection of Coal-Derived Synthesis Gas

Performer: University of Cincinnati and Missouri University of Science and Technology

Date: 04/01/2009 – 03/31/2012

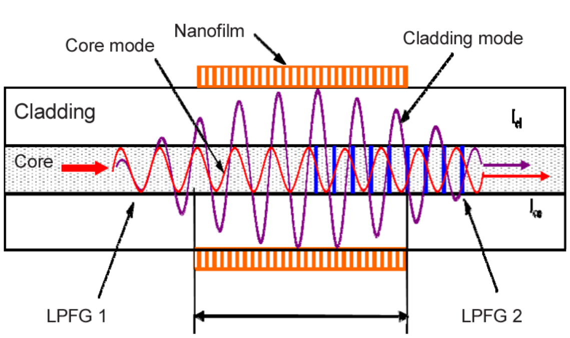
Cost: $326,958

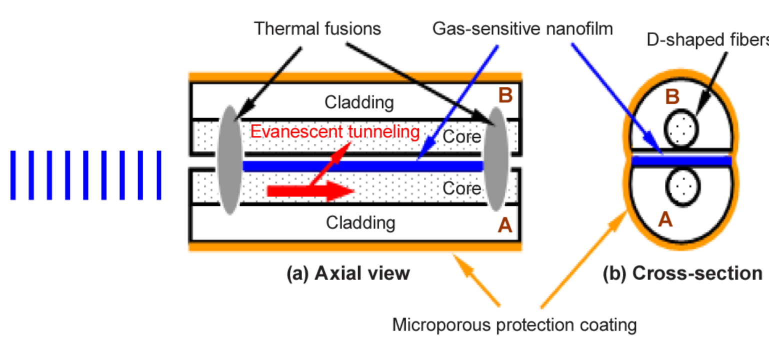
Technology Area: Optical Sensing

Program Area: University Coal Research

The overall objective of this project is to develop new types of high-temperature (>500 °C) devices for the monitoring of coal-derived gases by physically and functionally integrating advanced nano-ceramic materials with fiber optic chemical sensors (FOCS). This project also includes the development of sensors and sensor materials for hydrogen (H2), carbon dioxide (CO_2), and hydrogen sulfide (H2S) detection at temperatures greater than 500 °C and pressures up to 250 psi. The primary technical objective is to investigate and demonstrate two new types of nanocrystalline-doped ceramic-coated FOCS that possess the desired stability, sensitivity and selectivity for in situ, rapid gas detection in coal-derived syngas streams. The first type is a Long Period Fiber Grating (LPFG)-coupled self-compensating interferometer sensor and the second type is an evanescent tunneling sensor. For both types of sensors, high selectivity is targeted through the application of nanocrystalline thin film coatings of doped-ceramics that only interact with specific gas molecules and are inert to others. This project specifically focuses on sensors for H2 and H2S detection at high temperatures and elevated pressures. Fiber sensors have some proven advantages for various applications including their small/lightweight size, immunity to electromagnetic interference (EMI), resistance to chemical corrosion, high-temperature capability, high sensitivity, and their capability for remote operation.

The project will begin the model design of the LPFG-coupled interferometer and evanescent tunneling fiber sensors as well as the development of the nanocrystalline doped-ceramic materials suitable for gas sensing. Then it will be moved to the sensor fabrication (including integration of the nanofilm with fiber devices) and improvement of the ceramic nanofilm properties and fiber structures for enhancing sensor performance. Finally, the sensor performance in multicomponent gas mixtures under high temperatures and pressures will be evaluated. The three-year project involves interdependent research efforts in the areas of material, chemical, and electrical/optical engineering.





Conceptual designs for LPFG-coupled self-compensating interferometer sensor (left) and a nanocoated evanescent tunneling sensor (right). Figures provided courtesy of University of Cincinnati and Missouri University of Science and Technology.

Micro-structured Sapphire Fiber Sensors for Simultaneous Measurements of High Temperature and Dynamic Gas Pressure in Harsh Environments

Performer: Missouri University of Science and Technology, University of Cincinnati, and AmerenUE Corporate

Date: 10/01/2009 – 03/31/2011

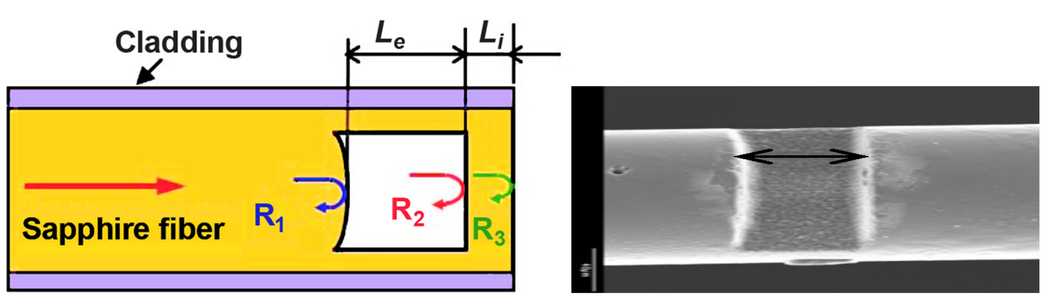
Cost: $1,131,799

Technology Area: Optical Sensing

Program Area: Coal Utilization Science

The focus of this project is to conduct fundamental and applied research leading to successful development and demonstration of robust, multiplexed, micro-structured sensors using single-crystal sapphire fibers. At the core of the technology are the hybrid extrinsic/intrinsic Fabry-Perot interferometer sensors directly micro-machined on a sapphire fiber using an ultrafast laser. This hair-thin, cylindrical filament made of single-crystal sapphire (glass) is able to transmit light by confining it within regions of different optical indices of refraction. These sensors can be deployed into the hot zones of advanced power and fuel systems (inside a coal gasifier or gas turbine system) to simultaneously measure high temperature (up to 1600 °C) and dynamic gas pressure.

The primary goal of this program is to develop and demonstrate multiplexed, micro-structured, single-crystal sapphire fiber sensors for temperature and gas pressure measurement in harsh environments. The project has three main objectives: (1) to incorporate sapphire fibers into sensors that are fully operational at high temperatures in a simulated harsh environment; (2) to develop and demonstrate novel sensors to simultaneously measure temperature and gas pressure in harsh environments; and (3) to develop and demonstrate novel sapphire fiber cladding and excitation techniques to assure high signal integrity and sensor robustness. The sapphire sensors being developed can help to produce affordable and clean energy from coal and other fossil fuels in an effort to secure a sustainable energy economy.



Conceptual design of micro-machined sapphire fiber for Fabry-Perot interferometer sensor for the measurement of temperature and pressure (left) and micro-machined silica fiber for conceptual evaluation (right). Figure and Photo provided courtesy of Missouri University of Science and Technology and University of Cincinnati.

Multiplexed Optical Fiber Sensors for Coal Fired Advanced Fossil Energy Systems

Performer: Virginia Polytechnic Institute and State University (Virginia Tech) and Alstom Power Plant Laboratory, Alstom Inc.

Date: 10/01/2008 – 09/30/2011

Cost: $1,065,195

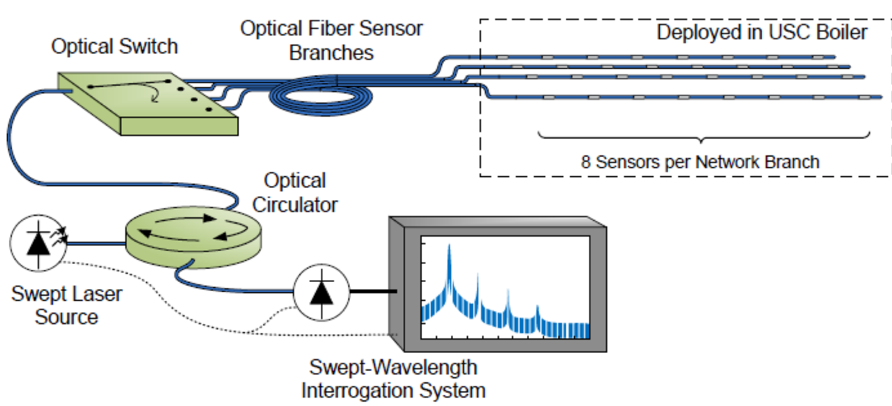
Technology Area: Optical Sensing

Program Area: Coal Utilization Science

The Center for Photonics Technology at Virginia Polytechnic Institute and State University (Virginia Tech) is developing distributed fiber optic sensors to measure strain, temperature, and pressure for conditions expected in the next generation of high-efficiency supercritical (SC) and ultra-supercritical (USC) boiler systems. Increases in efficiency of coal combustion to produce steam require increases in both temperature and pressure. More robust sensors are needed to monitor both fuel and steam-side atmospheres. Alstom's Power Plant Laboratory has teamed with Virginia Tech to develop sensors that can be distributed throughout a system to enable optimal performance. The sensors are constructed of protective materials to ensure reliable operation.

The project's multidisciplinary team began by identifying measurement requirements for fiber-optic sensors that monitor temperature, pressure, and strain in SC and USC boilers. Sensor designs are based on an intrinsic Fabry-Perot interferometer (IFPI)-type sensor that can be distributed along a single fiber in a single-mode-multimode-single-mode structure for measuring pressure, temperature, and strain. The team will create a sensor network designed to withstand conditions expected in the high-efficiency boiler systems for large-scale application.

Various IFPI sensor designs will be evaluated against the measurement requirements and multiplexed for the development of a sensor network. The project team will demonstrate the sensor network performance and survivability when exposed to simulated SC and USC boiler conditions.



Schematic of distributed and multiplexed fiber sensors. Figure provided courtesy of Virginia Polytechnic Institute and State University.

Novel Gas-Composition Sensor System for Monitoring Power Generation Systems

Performer: Physical Sciences, Inc. and the University of Wisconsin

Date: 06/01/2010 – 02/28/2011

Cost: $99,894

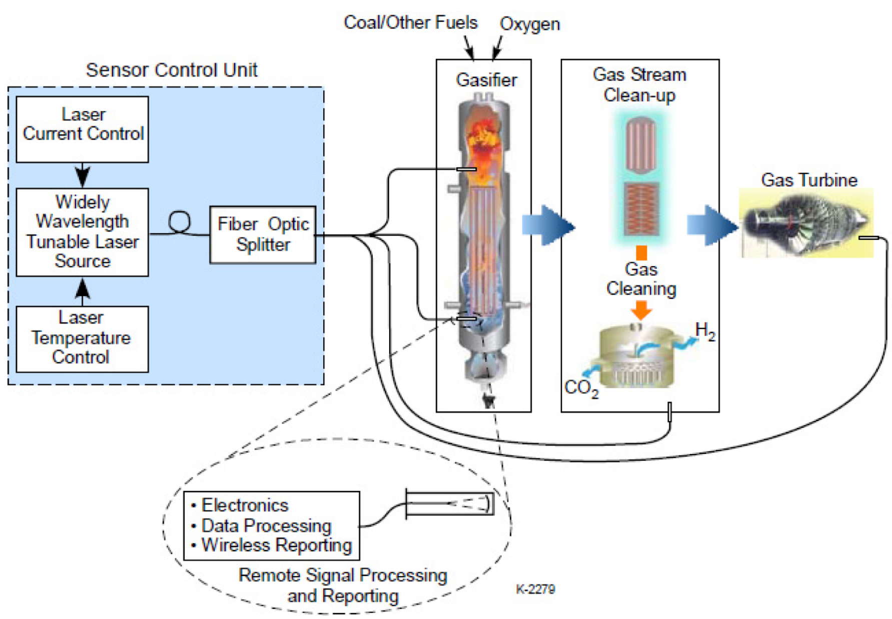
Technology Area: Optical Sensing

Program Area: Small Business Innovative Research

Physical Sciences, Inc. is collaborating with the University of Wisconsin to develop a spectroscopic sensor system for monitoring the concentration of multiple gas species in power generation systems. The system includes a sensor control unit that is fiber-optically multiplexed to a number of probes inserted into the harsh environment of power generation equipment such as coal gasifiers and gas turbines. The sensor system will be optimized for the high-pressure and high-temperature environment encountered in advanced power systems.

The objective of the combined Phase I and Phase II projects is to develop and demonstrate a novel sensor system for monitoring the concentration of multiple gas species in fossil-fuel combustion. The system is a combination of a broadly tunable laser with a high-temperature measurement probe, proprietary detection electronics, and data processing algorithms. The initial application target is the monitoring of full-scale, advanced power generation systems including coal gasifiers and gas turbines. The technology developed under this project may be applied to additional industrial processes, including continuous emission monitoring, pharmaceutical manufacturing, and explosives detection. The ability to identify multiple species and measure their concentrations in a gas mixture will allow manufacturers to increase yields and reduce costs.

Physical Sciences Inc. is also developing a novel laser-based system leveraging optical telecommunications technology for monitoring gas-species concentrations to improve efficiency and reduce emissions in combustion systems. The sensor system may also be used to measure emissions such as greenhouse gases, including carbon dioxide, produced by factories and vehicles.



Schematic of the multi-species multi-location gas composition sensor system. Figure provided courtesy of Physical Sciences, Inc.

Novel Modified Optical Fibers for High-Temperature, *in situ*, Miniaturized Gas Sensors in Advanced Fossil Energy Systems

Performer: Virginia Polytechnic Institute and State University (Virginia Tech)

Date: 06/01/2005 – 06/30/2011

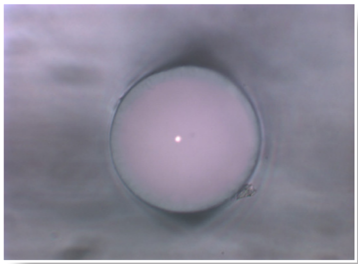
Cost: $1,187,364

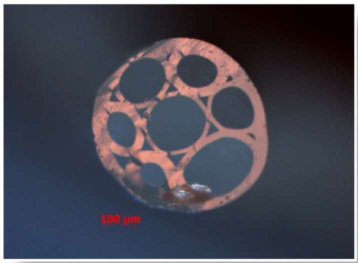
Technology Area: Optical Sensing

Program Area: Coal Utilization Science

Energy from coal-fired power plants will continue to play a dominant role in the energy landscape well into the future due to the abundant coal reserves available in the United States. Accurate and reliable detection of various gases is necessary for emissions monitoring and advanced process control in coal-fired power plants. Ideal gas sensors in these processes would operate *in situ*, exposed to high temperatures and harsh environments, where many conventional sensors cannot operate. Very few sensors are commercially available for high-temperature (1000 ºC) and harsh-environment monitoring of gases such as nitrogen oxides, sulfur oxides, carbon monoxide, hydrogen, oxygen, methane, and ammonia, which are present in coal and coal-derived syngas applications. These sensors suffer from a number of major limitations including limited accuracy, extremely short lifetimes, unexpected failure, and intensive maintenance.

Virginia Tech will develop novel, modified, fiber materials for high-temperature gas sensors based on evanescent wave absorption in standing hole optical fibers. In order to overcome the response-time limitation of current available holey fibers (due to gas phase diffusion constraints), a novel process is being developed to produce holes perpendicular to the fiber axis. This process uses the glass phase separation by spinodal decomposition to form three-dimensionally connected standing hole optical fibers. The presence of the gas molecules in the holes of the fiber appears as a loss of wavelengths characteristic to the particular gas species. Using a broadband source or spectral tuning of a laser source across key wavelengths permits the detection of multiple gases as well as establishing self-calibrating measurement capability. Researchers will investigate the feasibility of upgrading the technology to single-crystal sapphire by using sol-gel processing and performing laser backside photochemical etching, thereby advancing in the temperature capability of the gas sensor.





Examples of Porous Fibers: Solid core with porous cladding (left) and hollow cores with porous interfaces (right). Photos provided courtesy of Virginia Polytechnic Institute and State University.

Plasmonics-Based Harsh-Environment-Compatible Chemical Sensors

Performer: State University of New York at Albany, College of Nanoscale Science and Engineering

Date: 01/16/2009 – 01/15/2012

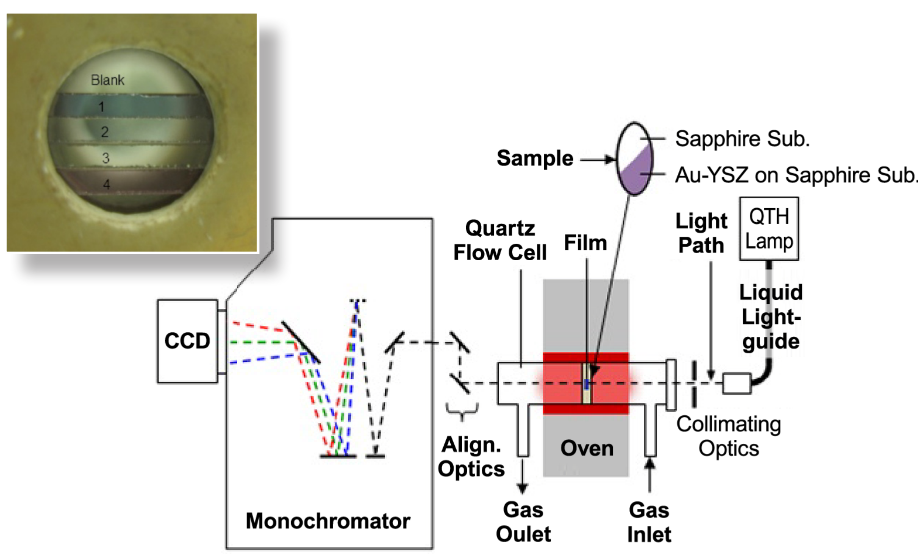
Cost: $432,230

Technology Area: Optical Sensing

Program Area: University Coal Research

Sensors and controls compatible with harsh environmental conditions are critically needed for use in gas turbines, solid oxide fuel cells, gas reformers, or other ancillary equipment in advanced power plants is a critical need. Currently available field-effect sensors based on silicon carbide or gallium nitride are unstable in a typical engine environment where temperatures can exceed 600 °C. Due to the complexity of material-incompatibility challenges, along with the intrinsic complexity of the field-effect device itself, a plasmonics-based all-optical sensing technique has been devised. A novel approach to gas sensing under harsh environmental conditions using the optical properties of tailored nanomaterials as the sensing layer is a much simpler design. This sensing system does not require the development of harsh-environment-compatible ohmic contacts, nor does it require high- temperature electronics, which typically suffer from reliability and stability problems.

The State University of New York at Albany will develop parallel materials-deposition techniques to engineer libraries of metal nanoparticles-based films with a metal-oxide matrix for rapid development of prototype sensing materials. The objective of this project is to further optimize these characteristics while developing a detailed understanding of the sensing mechanism as a function of temperature and humidity. Researchers will make a series of cross-selectivity measurements and exploring two approaches. Initial studies show the sensing response for the target gases to be dependent on the processing of the materials. For instance, the detection of carbon monoxide can be reduced by a factor of 20, while the detection of hydrogen is unaffected for the same film. The first approach will study the intrinsic cause of these sensing modifications, thereby enhancing the selectivity of these films toward nitrogen dioxide, carbon monoxide, and hydrogen. An alternative approach will be the use of a selective catalytic-reactive thin film to enhance the selective characteristics of these nanocomposite films. The development of these novel sensing materials would benefit advanced power systems by providing cost-effective sensors and control technology.



Conceptual example of a gas exposure bench and photo of fabricated plasmonic films. Figure and photo provided courtesy of State University of New York at Albany.

Real-Time Flame Monitoring of Gasifier Burner and Injectors

Performer: Gas Technology Institute (GTI), North Carolina State University, and ConocoPhillips Company

Date: 10/1/2002 – 12/31/2010

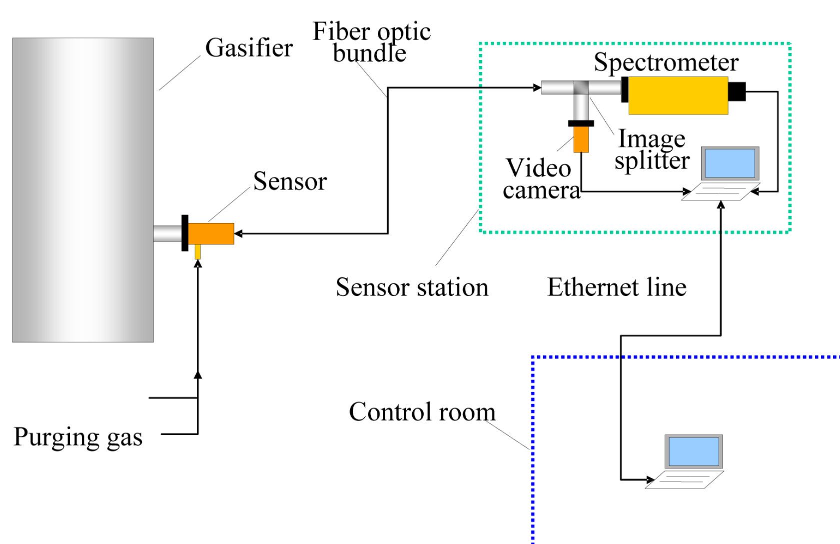
Cost: $1,683,394

Technology Area: Optical Sensing

Program Area: Advanced Systems – Integrated Gasification Combined Cycle

GTI, North Carolina State, and ConocoPhillips Company are collaborating to make ultra-clean gasification commercially competitive. The effort includes increasing the life of gasifier injectors which feed fuel into the gasifier. As injectors age and wear out, the flames they produce change. A reliable real-time flame monitor for gasifier injectors would allow gasifier operators to more accurately plan for injector replacement, thereby reducing maintenance costs and increasing gasifier reliability. The sensor data on flame characteristics may also assist in the development of better, longer-lasting injectors, which would also lead to gasifier operation savings. These sensors will allow furnace operators to manually adjust appropriate burner controls (e.g., flame length or firing rate), as well as maintain safe and stable combustion. However, the sensitivity and design of sensors make them incapable of measurements necessary for deeper qualitative and quantitative monitoring and analyses of complicated combustion processes, such as coal gasification.

This project focuses on the development of a sensor that goes beyond the capabilities of existing and emerging combustion sensors to produce a flame monitor to help minimize the maintenance costs of gasifier operation. The primary goal is to develop a reliable, practical, and cost-effective means of monitoring coal-gasifier feed-injector flame characteristics using a modified version of an optical flame sensor. The flame characteristics monitored by this sensor are flame shape, flame mixing patterns, flame rich/lean zones distribution, hydrocarbon oxidation dynamics, flame stability, and flame temperature. The sensor will be tested at lab scale on a natural gas flame, at bench scale in the vertical coal-slurry oxygen-enriched air combustor, and at pilot scale in an oxygen-fired, high-pressure slagging gasifier. The result of this project will be a simplified, industrially robust flame-characteristics sensor able to provide reliable information on the wear of coal-gasifier feed injectors, thereby improving injector life in coal gasification systems.



Conceptual Schematic of Sensor Installation on a Coal Gasifier. Figure provided courtesy of Gas Technology Institute.

Single-Crystal Sapphire Optical-Fiber Sensor Instrumentation

Performer: Virginia Polytechnic Institute and State University and Eastman Chemical Company

Date: 10/01/1999 – 08/31/2012

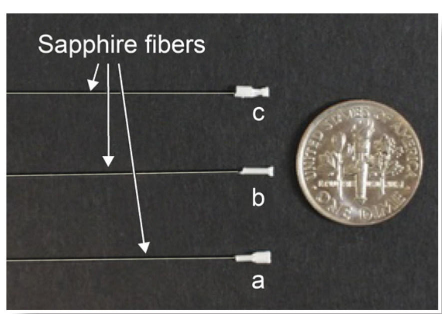
Cost: $3,993,893

Technology Area: Optical Sensing

Program Area: Advanced Systems – Integrated Gasification Combined Cycle & Coal Utilization Science

The Center for Photonics Technology at the Virginia Polytechnic Institute and State University (Virginia Tech) has developed a new, robust, accurate temperature-measurement system that can withstand the harsh conditions found in commercial gasifiers for an extended period of time, thus allowing improved reliability and advanced process control. While coal gasification offers a viable pathway to near-zero emission power generation, the conditions under which coal is gasified are harsh, including high-temperatures (1200 °C – 1600 °C), high pressures (up to 500 psi), and high rates of corrosion and erosion. The temperature sensor is based on single-crystal sapphire due to its high-temperature stability and resistance to corrosion. The sensor uses sapphire optical fiber and a sapphire disc joined to the end of the fiber to form the sensor. Light is launched and reflected back within the fiber to sense changes in temperature of the sapphire disc. The single-crystal sapphire allows optically-based measurement to be made and can fulfill the need for the real-time monitoring of high temperatures created in gasification processes.

The project includes fundamental research on high-temperature materials; design of optical temperature-measurement systems; and miniaturization and fabrication method development. The project also examines packaging of the fiber sensors for industrial use and testing of the sensor in full-scale gasifiers. The prototype sensor was subjected to a full-scale field-performance demonstration in 2006 and 2007. The sensor's performance under actual operating conditions was evaluated and optimized at temperatures up to 1400 °C. Initial testing was very successful as the sensor lasted seven months in the gasifier, surpassing an initial goal of around 45 days. In comparison, the thermocouples installed in proximity to the sensor had to be replaced at least twice during the seven month period.



Single-crystal sapphire sensor heads with the sapphire fiber waveguides achieve greater precision through miniaturization. Photo provided courtesy of Virginia Polytechnic Institute and State University.

Tunable Diode Laser Sensors to Monitor Temperature and Gas Composition in High-Temperature Coal Gasifiers

Performer: Stanford University and University of Utah

Date: 10/01/2009 – 9/30/2012

Cost: $1,097,321

Technology Area: Optical Sensing

Program Area: Coal Utilization Science

Stanford University and the University of Utah are working together to design, build, and test a tunable diode laser (TDL) sensor capable of measuring gas concentrations and temperature in a gasification system. The laser sensor is currently being tested in laboratory and pilot scale facilities to determine the conditions and locations in the gasification system in which the sensor can operate. Test data will enable Stanford to better understand the sensor performance in full-scale gasification systems. Two crucial sensor needs for the production and utilization of syngas have been identified: (1) to control the temperature of the gasifier by adjusting feed rates of fuel and oxygen to the gasifier, and (2) to control the air dilution at the intake to the gas turbine. To address these needs, the laser-based sensor aims to measure H_2O, CO, CO_2, and CH_4 concentrations in the high-temperature, high-pressure gasifier environment. CO and CO_2 concentrations have the potential to be used as control variables for the gasifier as well as for the subsequent utilization of the syngas (e.g., in a gas turbine). The CH_4 concentration in the output syngas stream often serves as a surrogate monitor of gasifier temperature. However, the TDL sensor will measure in situ the real-time gas temperature from the ratio of absorption of selected H_2O absorption transitions.

The project's first phase – Sensor Development – focuses on developing the laser sensor and fabricating optical access downstream of the gasifier reactor. The second phase – Sensor Testing – will evaluate sensor performance in the main reaction section of the gasifier. Lessons learned from the first phase have been used to make improvements to the laser and optical access design.

The ability to scale sensor performance from the pilot-sized reactor at the University of Utah to various potential commercial designs requires understanding sensor performance as a function of particulate loading and gasifier pressure. The researcher will develop scaling rules needed to estimate sensor performance in other environments (e.g., different gasifier designs or operating conditions).

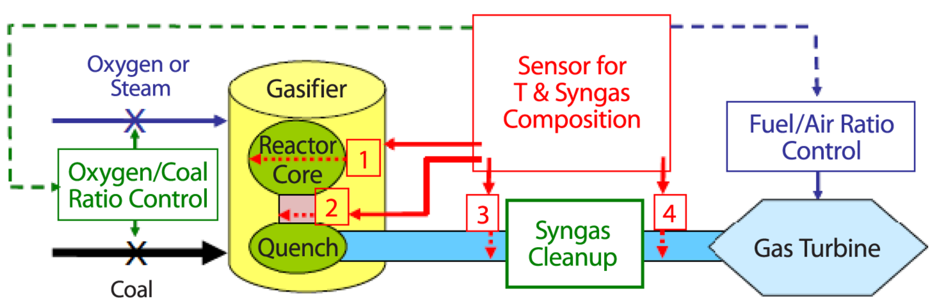


Illustration of the potential locations of gas sensors for control of a combined-cycle power plant. Figure provided courtesy of Stanford University and University of Utah.

Condition-Based Monitoring Of Turbine Combustion Components

Performer: Siemens Energy, Inc., K Sciences GP, LLC, Philtec Inc. and JENTEK Sensors, Inc.

Date: 10/01/2008 – 09/30/2011

Cost: $1,673,417

Technology Area: Optical Sensing

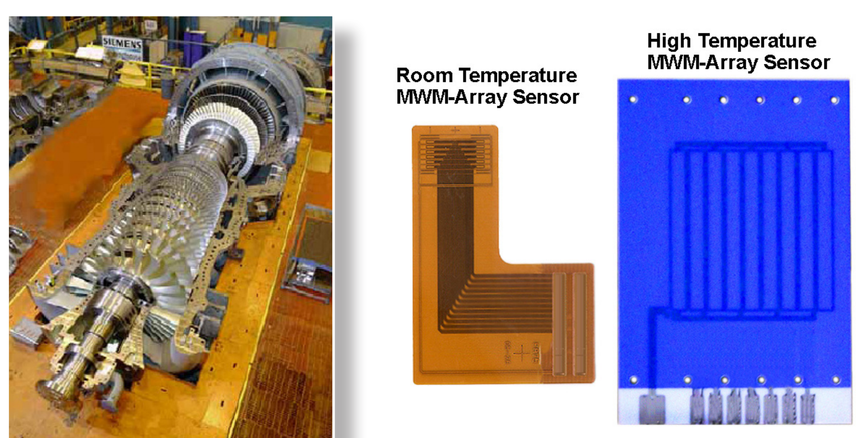
Program Area: Coal Utilization Science

Siemens Energy is leading an effort to develop an integrated condition monitoring system for turbine components. The overall goal of this work is to implement an advanced condition-based maintenance approach that extends the operating time of turbine systems and improves the overall control of the turbine system. The research team is developing sensors to directly assess the condition of critical parts, specifically wear and crack formation at high temperatures (1000–1300 °C); this task cannot be done with current commercially available sensors.

Researchers are using a fiber-optic approach to perform wear measurement, mounting the fiber at the wear surface to continually monitor wear and wear-progression at the contacting faces. The wear sensor has a targeted operating temperature of 1000 °C. Cracking is being monitored by the deployment of a multi-functional high-temperature magnetic sensor developed at JENTEK Sensors, Inc. This sensor uses magnetic fields to continuously monitor crack progression while correcting for temperature variations. The materials and construction of this sensor will be modified to allow operation at temperatures of 1000 °C. The algorithms deployed to monitor cracks and compensate for temperature variations are being developed to allow crack monitoring at high temperatures.

The objective of this work is to design, develop, and demonstrate a condition-monitoring sensor network comprising a high-temperature wear sensor and multi-functional magnetic sensor to monitor cracks in hot section combustion components in real time. The wear- and crack-monitoring sensors are being combined with the basic control system sensors to provide a modular sensor network for condition monitoring and assessment of combustion hardware.

The prototype sensors have passed laboratory proof-of-concept tests. The testing demonstrated the wear sensors' capability to provide a stable, repeatable output with 0.12 mm resolution, surviving at high temperatures in short term tests. The crack sensor successfully detected crack growth and surface temperatures of test specimens. Additional validation tests at high temperatures are in progress. After completing sensor life and performance assessments, prototype demonstration tests will be accomplished in an engine environment. The sensors will provide an integrated sensor network for condition monitoring of hot section parts.



Examples of a combustion turbine (left) and crack detection sensors (right). Photos provided courtesy of Siemens Energy and Jentek Sensors, Inc.

Distributed Fiber Optic Sensor for On-Line Monitoring of Coal Gasifier Refractory Health

Performer: Virginia Polytechnic Institute and State University (Virginia Tech)

Date: 1/18/2011-1/17/2014

Cost: $1,460,138

Technology Area: Optical Sensing

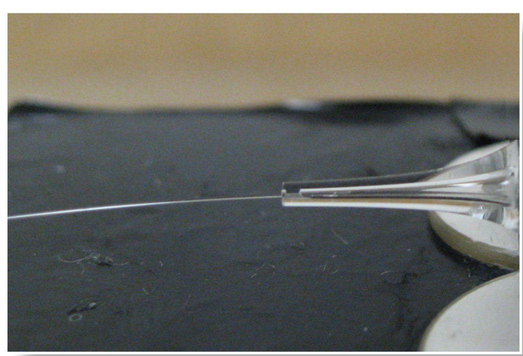
Program Area: Coal Utilization Science

Recent advances in fossil fuel energy production technologies have shown tremendous potential to efficiently create clean, sustainable electricity using a variety of carbon rich fuels. Techniques such as the Integrated Coal Gasification Combined Cycle (IGCC) have been demonstrated as feasible next-generation energy sources, but commercial operation of these facilities poses significant challenges. Foremost among these difficulties is the issue of refractory wear. The high-temperature reducing environment in the gasifier causes rapid corrosion of even the toughest refractory materials, limiting typical useful lifetime. Furthermore, the complexity and uncertainty of the gasification process makes remaining refractory life difficult to predict in working gasifiers.

To address this concern, this project will develop an advanced distributed sensing technology capable of monitoring refractory wear in an operating coal gasifier. The Virginia Tech Center for Photonics Technology (CPT) will develop a prototype sensing system and evaluate it in a laboratory test environment for operation at temperatures over 1000 degrees Celsius (°C).

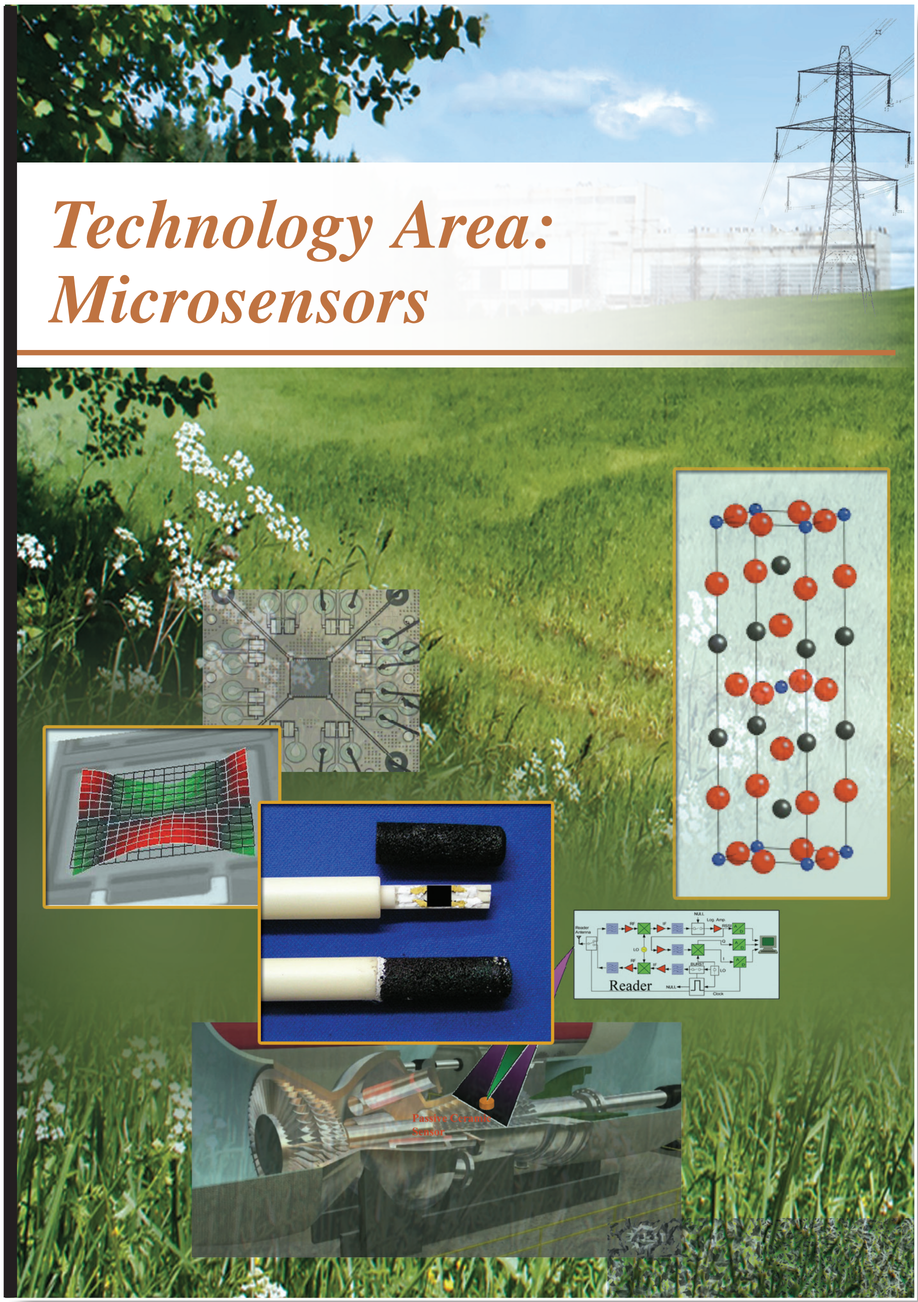
The project's objective will be met through development of a basic numerical model of the thermal effects of refractory degradation. The model will then be used to guide the design of the sensor and simulated test environment. CPT will develop a basic computational model to describe the thermal properties of specific refractory breakdown phenomena, from which the high-temperature distributed sensor technology can be used to pinpoint weak spots in the refractory liner and evaluate remaining lifetime. Numerical output will be compared to the laboratory test results and used to confirm the sensor's ability to monitor refractory health.

By providing the capability for comprehensive on-line monitoring of refractory health, the proposed technology will ultimately improve gasifier availability and reduce the frequency of refractory maintenance through condition-based assessment. The direct measurement technology will enable early detection of hot spots in the refractory wall and measurement of its remaining lifetime, leading to improved performance, longevity, and cost savings. Use of the distributed sensor will allow gasifier operators to adopt a conditions-based maintenance model, reducing the need for frequent shut-downs.



Concept Validation Setup

Technology Area: Microsensors



Adaptable Sensor Packaging for High-Temperature Fossil-Fuel Energy Systems

Performer: Sporian Microsystems, Inc.

Date: 06/27/2005 – 08/06/2010

Cost: $1,046,803

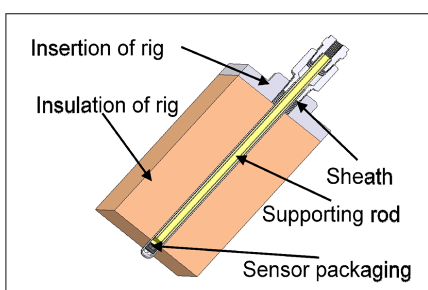
Technology Area: Microsensors

Program Area: Small Business Innovative Research

Advanced, integrated control systems will be essential to achieving the cost and performance targets of high-efficiency, low-emissions fossil-fuel plants. Micro-electro-mechanical systems (MEMS) and other types of microsensors will play an important role by providing critical real-time measurements needed to optimize these processes. Although microsensor technologies have been demonstrated, better packaging is needed that will protect the microsensors from harsh environments; allow the sensors to be exposed to the gas stream; and interface the sensors with high-temperature electronics, housings, and hardware. This project is to develop a standard, engineered testing package, with an integrated protective housing, for applying microsensors to high-temperature turbine applications. The focus of work is on the proper selection of materials with silicon carbonitride as the base material, followed by design of a package for turbine applications and testing of the integrated sensor assembly.

The technical approach is to leverage established ceramic microelectronics packaging and high-temperature thermocouple concepts by using proper design and material selection. During Phase I, researchers developed a design framework for a general-purpose high-temperature sensor package and conducted experiments to evaluate feasibility. Phase II involves the development of a prototype, standard, engineered testing package. Specific tasks include (1) developing key structural components; (2) developing and testing high-temperature electrical interconnect and "die attach" technologies; (3) final design and fabrication of a prototype package; and (4) the experimental demonstration of the prototype in high-fidelity laboratory testing and external-stimulant application test systems.

The sensor packaging technology would allow end-application integrators, such as gas turbine and fuel cell manufacturers, to realize the benefits associated with the advanced sensors. These sensors could be designed into their equipment using a common, standardized packaging infrastructure. In addition to energy generation, a low-cost, high-reliability packaging for harsh environments would be useful in a wide range of other commercial applications such as propulsion, aerospace, automotive, and military. The public as a whole would benefit from reduced emissions, enhanced efficiency, and overall lower operating costs.



Conceptual design of packaged sensor for turbine application using silicon carbine nitride materials (left) and an example of silicon-carbide-nitride porous protection cap and supporting rod. Figure and photo provided courtesy of Sporian MicroSystems, Inc.

Development of Electrochemical Sensors for Fossil Energy Applications

Performer: Oak Ridge National Laboratory (ORNL)

Date: 04/01/2008 – 12/20/2012

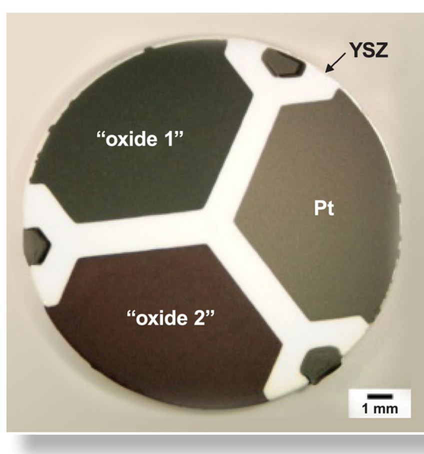
Cost: $450,000

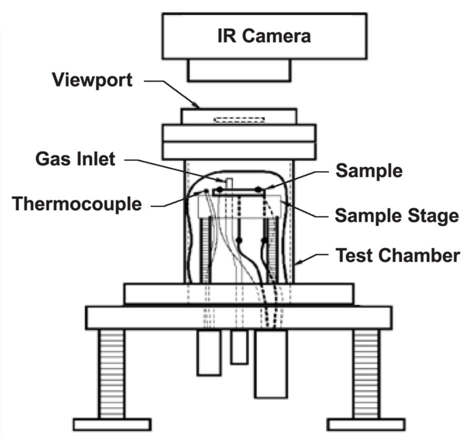
Technology Area: Microsensors

Program Area: Coal Utilization Science

Oak Ridge National Laboratory's goal is to develop a low-cost electrochemical sensor based on mixed potential phenomena able to detect sulfur oxides at temperatures in the range of 500–800 °C. An additional goal is to design sensors to allow them to be placed anywhere from the cold flue gas to the hot zone to facilitate improved control of combustion processes. Since coal often contains sulfur, these sulfur oxides are generated during combustion. Measurement of sulfur dioxide (SO_2), in particular, is important in relation to environmental pollution, occupational and public heath, and industrial emissions control because it can be toxic in large amounts.

Currently, ultraviolet fluorescence is widely used to monitor SO_2 emissions. This technique offers excellent precision and selectivity, but requires complex and expensive instrumentation. It also requires the gas to be cooled to near room temperature, introducing difficulties due to condensation. Electrochemical sensors have the potential advantages of ease of fabrication, high sensitivity, rapid response, on-line monitoring, and feasibility for miniaturization. However, numerous approaches investigated in the last five years to measure SO_2 concentrations in gas streams have not resulted in a viable sensor. The objective of this research project is to develop compact and inexpensive SO_2 sensors that can operate at high temperatures. Realization of such sensors would offer the following advantages: eliminating the need to cool the exhaust gas, enabling operation closer to the combustion zone, and reducing cost of the sensor.





Prototype of mixed potential sensor array (left) and sensor test thermographic apparatus (right). Photos provided courtesy of the University of Utah.

Development of High-Temperature, High-Sensitivity Novel Chemical-Resistive Sensors

Performer: University of Texas at San Antonio

Date: 09/01/2010 – 08/31/2012

Cost: $200,000

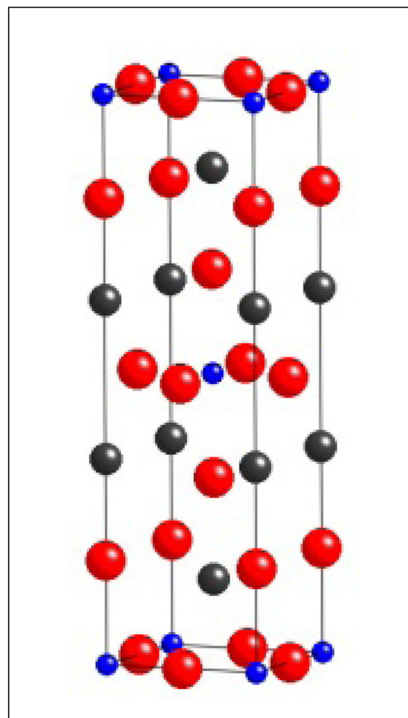
Technology Area: Microsensors

Program Area: Historically Black Colleges and Universities (and Other Minority Institutions) & University Coal Research

The University of Texas at San Antonio's goal is to design, fabricate, and develop novel high-temperature, high-sensitivity, multifunctional chemical sensors for the selective detection of fossil-energy gases in power and fuel systems. Researchers will explore and use the advantages of the thin film referred to as LBCO (LnBaCo2O5+d where Ln=Pr or La) to develop high-temperature chemical-resistive sensors. Highly epitaxial single-crystalline LBCO thin films are chemically stable at high temperature (>800 °C), and extremely sensitive to various oxidizing/reducing environments with very short response time (<0.1 seconds) and ultra fast surface exchange kinetics (extremely low activation energy of 0.26 electronvolts). These characteristics suggest that the LBCO thin film is an excellent candidate for the fabrication of sensors and control systems for power- and fuel-monitoring systems. The final objective of this research is to determine the overall feasibility of the LBCO-based novel electrochemical devices for sensing gases in high-temperature applications.

Details of the research include the following: (1) the systematic study of the physical properties and chemical stability of the highly epitaxial LBCO thin films; (2) characterization of the LBCO thin films at high temperature (>700 °C) for sensing the various gas compositions to allow precision analysis and control of these parameters; (3) design and fabrication of various LBCO thin-film-based chemical-resistive sensors for monitoring the gas composition at high temperature; and (4) theoretical and modeling studies on the absorption, reactivity, and stability of the LBCO thin films to understand thin-film chemical behavior in the target high-temperature range.

Researchers will test the device performance by systematically investigating various gas compositions, poison resistance, and cross sensitivity. These novel sensors will aid in the development of the next-generation highly efficient, near-zero emission power generation technologies.



Conceptual structure of LBCO Material. Figure provided courtesy of University of Texas at San Antonio.

Harsh-Environment Gas-Composition Sensors Using Novel Silicon-Carbide (SiC) Resonant Resonant MEMS

Performer: Boston Microsystems, Inc.

Date: 06/01/2010 – 03/18/2011

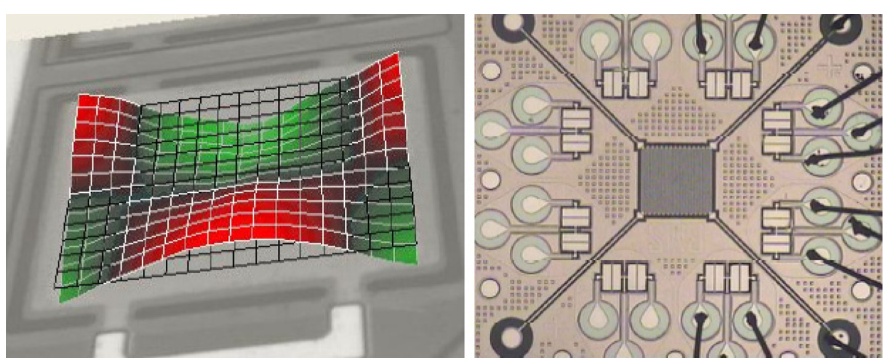
Cost: $100,000

Technology Area: Microsensors

Program Area: Small Business Innovative Research

Future power generation systems including advanced combustion, coal gasification, fuel cells, and biodiesel fuel will require real-time measurement of both constituent gas components and contaminants to operate both cost-effectively and with minimal levels of harmful emissions. However, the extreme temperatures, pressures, and corrosive environments in which these sensors must operate have seriously impeded their development and commercialization. Boston MicroSystems previously developed and demonstrated microresonator-based chemical detectors manufactured from silicon carbide, aluminum nitride, and refractory platinum electrodes, which can detect a wide range of chemicals in complex and varying backgrounds. More recently, it was shown that these sensors function at the elevated temperatures (>500 °C) found in diesel-combustion exhaust streams. Specifically, nitrogen oxides which contribute to smog and acid rain can be detected; therefore, these sensors could be used to enable real-time nitrogen-oxide pollution control systems. This project seeks to extend the application of silicon carbide-aluminum nitride micro-electric-mechanical-systems resonators to the high-pressure environments found in advanced power systems, including clean coal and biodiesel synthetic gas production. The technical innovation is a novel flexural plate-wave (FPW) device that is able to function as a mass-sensitive resonator at high temperatures and pressures. This project is to build, test, and evaluate the performance of an FPW sensor designed to measure concentrations of fossil-fuel-component gases operating at 500 °C and 800 psi, conditions representative of real-world coal gasification environments.

A multi-analyte gas sensor able to operate in high-pressure and high-temperature conditions would contribute significantly to the development of advanced energy systems. Successful deployment of these systems would help mitigate the economic impact of increased costs of fossil fuel, reduce U.S. dependence on foreign energy sources, and ensure a safer environment by reducing the output of greenhouse gases and other harmful emissions.



Micrograph of one SiC-AlN resonator with laser vibrometry image of its (2,1) resonance mode (left), micrograph of the SiC-AlN resonator array with 8 resonator sensors (right) Figures provided courtesy of Boston Microsystems, Inc.

Investigation of Tungsten Oxide-based Hydrogen Sulfide Sensor Materials for Coal Gasification Systems

Performer: University of Texas – El Paso (UTEP)

Date: 01/15/2009 – 01/15/2012

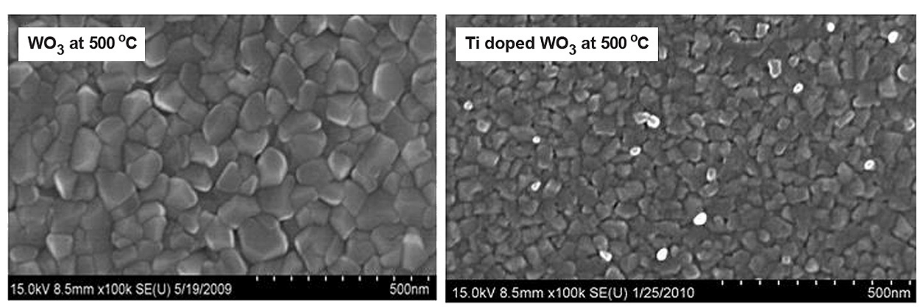
Cost: $199,546

Technology Area: Microsensors

Program Area: Historically Black Colleges and Universities (and Other Minority Institutions)

The University of Texas – El Paso (UTEP) will investigate tungsten oxide (WO_3)-based nanomaterials for use to detect hydrogen sulfide (H_2S) gas in coal gasification systems. The objective of the project is to develop high-quality new sensor materials for achieving improved response time and controlled microstructure for long-term stability, and to narrow particle-size distribution for improved sensor characteristics and performance. Researchers will identify methods to enhance the so-called 3S criteria—sensitivity, selectivity, and stability—by controlling the structure and properties of these materials at nanometer dimensions. Two main areas of investigation are H_2S detection selectivity, sensitivity and stability of undoped and titanium-doped WO_3 and the surface functionalization and stabilization of WO_3 by metals such as gold and aluminum for H_2S sensors. Sensors are being studied at moderate concentrations of H_2S (nominally 5–100 ppm H_2S in nitrogen), using parameters that simulate a real environment with service temperature of approximately 200–600 °C.

Researchers will systematically study the effect of processing conditions on the growth and microstructural evolution of undoped and doped WO_3 thin-films and nanostructures using X-ray diffraction (XRD), scanning electron microscopy, atomic force microscopy, energy dispersive X-ray spectrometry, Fourier transform infrared absorption, Raman, and X-ray photoelectron spectroscopy. Understanding the structure-property relationships and electronic structure changes associated with the oxide surfaces will permit the development of stable microstructures to address long-term stability and H_2S selectivity issues. This comprehensive suite of measurements, together with temperature-dependent electrical characterizations and performance evaluation tests, will be used to assess the feasibility of titanium-, gold-, and aluminum-doped WO_3 materials for detecting and monitoring H_2S in coal gasification systems.



SEM Pictures of Tungsten Oxide (WO_3) and WO_3 doped with Titanium nanomaterials. Photos provided courtesy of University of Texas at El Paso.

On-Line, *in situ* Monitoring of Combustion Turbines Using Wireless, Passive, Ceramic Sensors

Performer: University of Central Florida

Date: 01/01/2010 – 12/31/2012

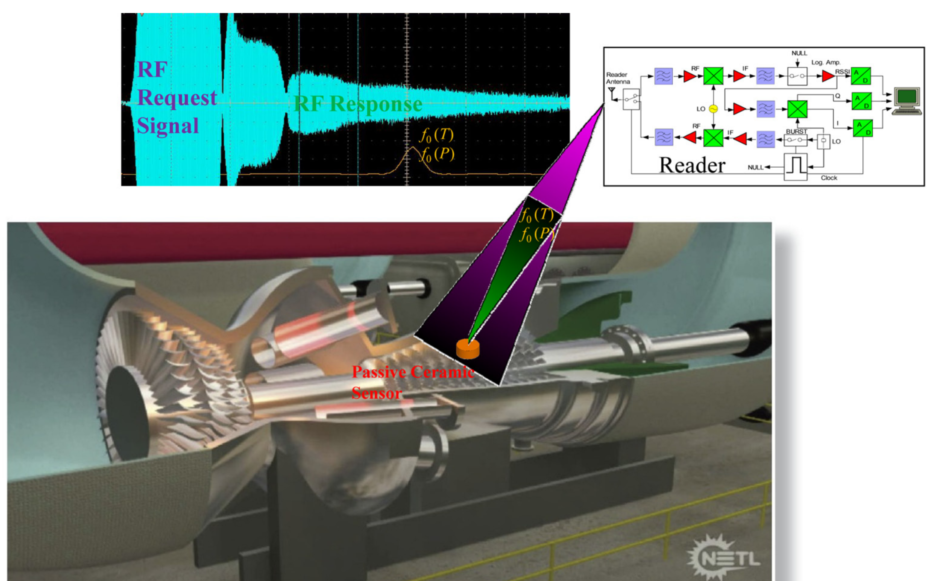
Cost: $1,013,994

Technology Area: Microsensors

Program Area: Coal Utilization Science

Advanced, near zero-emission power systems currently under development require sensing and control technologies that allow real-time, *in situ* monitoring of system operations involving highly automated process controls. For gasification plants to be more efficient and less costly, sensors used in the process need to be sturdier and more accurate than those currently available. Researchers at the University of Central Florida are developing wireless, passive, ceramic microsensors for *in situ* temperature and pressure measurement inside combustion turbines. These sensors are being designed to operate in high-temperature (>1300 °C), elevated-pressure (300–700 psi), harsh environments. The primary objective of this project is to develop a set of high-temperature, wireless, passive, ceramic, micro-electro-mechanical systems (MEMS) sensors for on-line, real-time monitoring applications in turbine systems. The project team is providing precise operational parameters in real-time for optimal system control, higher efficiency, increased reliability, and improved emissions.

The development of sensors and controls capable of withstanding high-temperature and high-pressure conditions will help integrate and optimize complex power systems. The sensors being developed under this project possess specific advantages when compared to existing sensors, including these attributes: (1) wireless, (2) passive, (3) accurate, (4) robust, (5) of very small size, and (6) having the ability to network with other sensors. These features permit sensor placement in areas in which it is difficult or impossible to place existing sensors and they enable simultaneous readings by multiple sensors connected to a single display. Their use in combustion turbines will facilitate the use of gasification plants to produce power from various fuels cleanly and efficiently.



Targeted application of sensors: advanced combustion turbine and example of resonant frequency of the ceramic sensor which contains temperature or pressure information. Figure provided courtesy of NETL and University of Central Florida.

Multifunctional Nanowire/Film Composites Based Bi-Molecular Sensors for High-Temperature Gas Detection

Performer: University of Connecticut

Date: 10/01/2009 – 9/30/2012

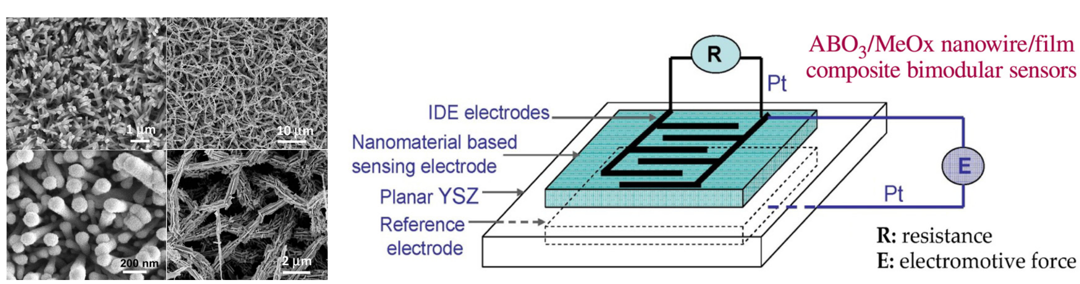
Cost: $1,010,772

Technology Area: Microsensors

Program Area: Coal Utilization Science

Real-time monitoring of the composition of combustion gases usually requires sensors to be operated at high temperatures in harsh environments. Currently, commercially available sensor technology capable of withstanding such harsh environments is extremely limited; therefore, there is an urgent need to develop novel high-temperature gas sensors. Researchers at the University of Connecticut are developing a unique class of multifunctional metal oxide/perovskite-based composite nanosensors for industrial and combustion gas detection at high temperature (700-1300 °C). A sensing platform is being designed and fabricated with an array of integrated electro-resistive and electrochemical nanosensors to meet the challenge of gas detection in high-temperature, complex gaseous environments in various combustion conditions. The miniaturized platform is bi-modular, and made up of three-dimensional (3-D) nanowire/dendrite arrays and two-dimensional (2-D) composite nanofibrous thin film. The 3-D and 2-D composite architectures are assembled by single-crystal 3-D nanowire/nanodendrites or polycrystalline 2-D nanofibrous films made of multifunctional metal oxides. These nanocomposites combine the functions of wire/dendrite arrays and thin film to increase the nanosensors' sensitivity to catalysts, stability at high temperatures, and ability to detect multiple gases.

The goal of the project is to advance the gas-detection field by developing high-temperature, *in situ* and real-time gas sensors using a unique class of multifunctional metal oxide/perovskite core-shell composite nanostructures for industrial and combustion gas detection. The specific objectives are to synthesize metal oxide-based nanowire/film composites; to determine and optimize the deposition parameters for growth of nanowire/film composites; to investigate nanowire/film composites; to design and fabricate bi-modular nanosensors using the nanowire/film composite nanostructures; to characterize the resistive detection module and the potentiometric detection module of the nanosensors in different high-temperature, gaseous environments; and to establish their corresponding calibration curves. The bi-modular gas sensor developed through this project will be more robust and provide more information than sensors currently available for harsh conditions at high temperature. Good selectivity, fast response, and enhanced sensitivity in high-temperature gas detection can be achieved by these nanosensors due to the diversity of the nanomaterials, the inherent large specific surface area of nanostructures, and minimized gas diffusion resistance.



Metal oxide-based nanowire/film assembly (left), conceptual microsensor design for testing nanowires/films (right). Photo and figure provided courtesy of the University of Connecticut.

Condition-Based Monitoring of Turbine Blades Demonstrated in H-Class Engine

Performer: Siemens Energy, Inc

Date: 1/30/2011 – 1/29/2014

Cost: $1,685,746

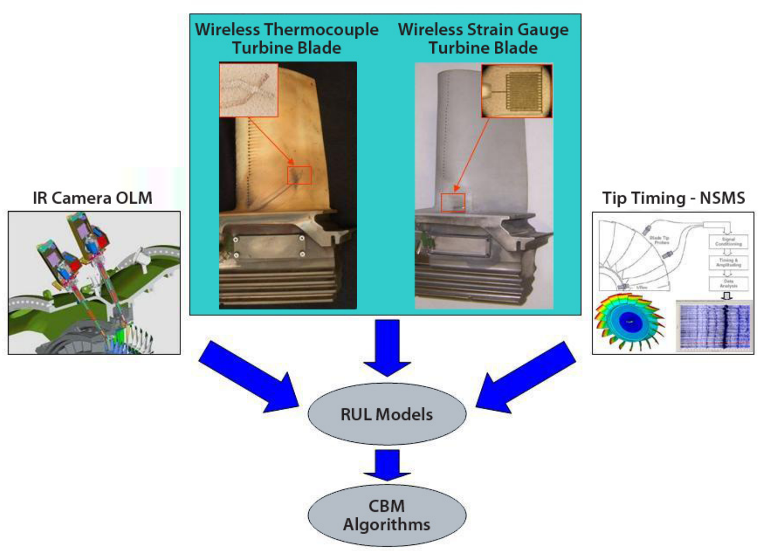
Technology Area: Microsensors

Program Area: Coal Utilization Science

Electrical power generation relies on the use of turbomachinery to provide highly efficient and reliable power. One of the major components of the turbine that is essential are the blades used in the hot high velocity environment inside the turbine. The blade performance and condition are directly related to the efficiency and reliability of the turbomachinery. Real-time monitoring of component condition and accurate information concerning component remaining life is essential for a transition from schedule-based maintenance (current practice) to condition-based maintenance.

To address this concern, Siemens Energy, Inc. will develop Smart Turbine Blades based on technology designed to build self-aware engine components that incorporate embedded harsh-environment-capable sensors and high-temperature-capable wireless telemetry systems for continuously monitoring component condition in both the compressor and turbine sections. The Smart Turbine Blades will have incorporated on their surfaces thermally sprayed thermocouples and dynamic strain sensors capable of operating at up to 1250 degrees Celsius (°C). An embedded, high-temperature wireless telemetry system capable of operating at 450 °C will be located near the hot section of the turbine. The project team will install wireless Smart Turbine Components and integrate the data with the remaining useful life (RUL) models and Power Diagnostics® engine monitoring program.

Combining fast area sensors with point sensors (such as thermally sprayed thermocouples and dynamic strain gauges connected to wireless transmitters) to enable a real-time, high-accuracy remote monitoring of rotating turbo-machinery will enable true On-line condition-based maintenance procedures to be realized, and will ultimately transform how land-based turbines are designed, optimized, and operated, as well as how they are maintained.



Overview of Real-Time, High-Accuracy Remote Monitoring of Rotating Turbo-Machinery

the ENERGY lab


Technology Area:
Advanced Process Control
Reducer Loop
Reactor Column
Secondary Cyclones
Seal Pot and Solids Control Device
Solids Pick-up and Transition Section
Chemical Looping Primary Process Loops
Sensor Suite
Control Actuation

Development of Computational Approaches for Simulation and Advanced Controls for Hybrid Combustion-Gasification Chemical Looping

Performer: Alstom Power, Inc. and University of Illinois Urbana-Champaign

Date: 07/12/2007 – 03/31/2011

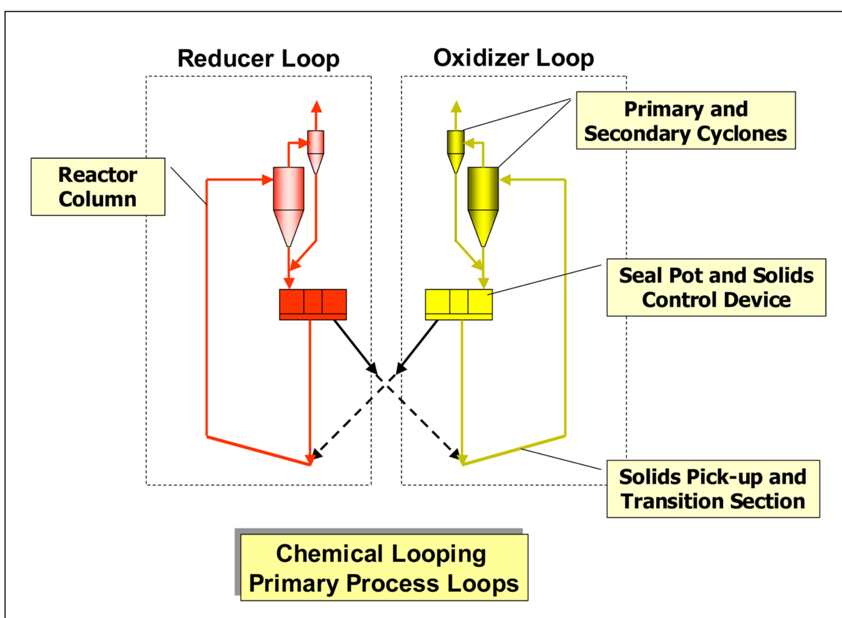
Cost: $1,993,281

Technology Area: Advanced Process Control

Program Area: Coal Utilization Science

Research toward developing the Hybrid Chemical Looping (CL)-based plant concept, application of advanced sensors, and optimizing control methods will contribute to DOE's goal of advanced near-zero emission, highly efficient, coal-based power generation systems. This project is to develop model-based controls that can be used to operate the system. The goal is to develop advanced multivariable optimizing controls integrated early into the process development cycle to ensure a controllable and reliable plant-level design. The objective is to build upon the existing state-of-the-art CL technology. The research team will use Alstom's CL test facilities to develop an understanding of the complex process dynamics and sensor and control needs of CL processes; to build simple process simulation models with dynamic capability suitable to evaluate control methods; and to develop a method for proactive integration of advanced controls into the Hybrid CL plant-design process to optimize the process and controls. Researchers will investigate advanced sensors and process control and analysis methods for CL, application to complex solids-flow and gas-pressure controls in the interacting multiple-loops, and implementation into a total plant integrated control concept. The team will also begin to develop an Advanced Process Control System design concept that can be used as a starting point for design and implementation of the control system for the future Hybrid CL prototype facility project.

The team's approach is to integrate controls early in the process development timeline and to demonstrate model development, reduction, and the comparative benefits of model-based control versus Proportional-Integrated-Derivative control. Benefits include a detailed process to develop and integrate advanced control into process design and development.



Conceptual schematic of the loops in the primary process chemical looping. Figure provided courtesy of Alstom Power, Inc.

Distributed Sensor Coordination for Advanced Energy Systems

Performer: Oregon State University

Date: 11/01/2009 – 10/31/2012

Cost: $887,606

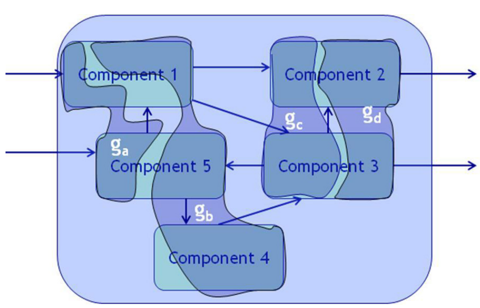
Technology Area: Advanced Process Control

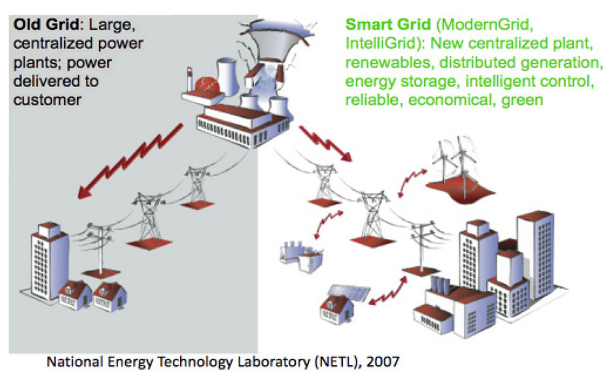
Program Area: Coal Utilization Science

As advanced energy systems grow in size, they require an increasing number of pressure, temperature, and composition sensors for optimal control and operation. In many cases, communication of individual sensors with a central controller is inefficient. In this project, Oregon State University researchers are developing control algorithms to manage a network of sensors that can collect and process data and provide key control decisions. The project focuses on developing a sensor algorithm that leads to a good network-wide solution, while allowing individual sensors to function independently. The project derives, implements, and tests agent-objective functions that promote coordinated behavior in large sensor networks. The long-term objective is to provide a comprehensive solution to a scalable and reliable sensor coordination problem leading to safe and robust operation of advanced energy systems.

Project work is focused in two areas, including deriving criteria for assessing the impact of sensor locations and objectives, and demonstrating the effectiveness and reconfigurability of sensors in response to a change in performance criteria. Achieving these objectives requires quantifying the effectiveness of various sensor configurations. The project directly evaluates the impact of information quantity on the effectiveness of the sensor configurations and quantifies the amount of global information necessary for different sensor configurations to effectively assess the state of the system.

A successful demonstration of this technology can lead to reliable, robust, scalable, and reconfigurable sensor networks, which can enhance the efficiency of advanced power systems through more precise control. In an advanced energy system, sensor networks allow information to be collected more efficiently, respond more quickly to sudden developments, and allow for autonomous system reconfiguration. In addition, the smart sensor coordination algorithms also provide other benefits to the DOE and the U.S. government through their use in a smart power grid, coordinated search and rescue, and self-organizing nano/micro devices.





Algorithms automatically group sensors into subsystems selected to optimize each group individually for the best overall system performance (left). The same underlying algorithmic approach can also be used with large scale distributed systems such as new smart grid technologies where delivering electricity from suppliers to consumers using two-way digital technology to control appliances at consumers' homes to save energy and reduce cost (right). Figures provided courtesy of Oregon State University.

Development of Model Based Controls for GE's Gasifier and Syngas Cooler

Performer: General Electric Global Research

Date: 07/05/2007 – 03/31/2011

Cost: $3,016,848

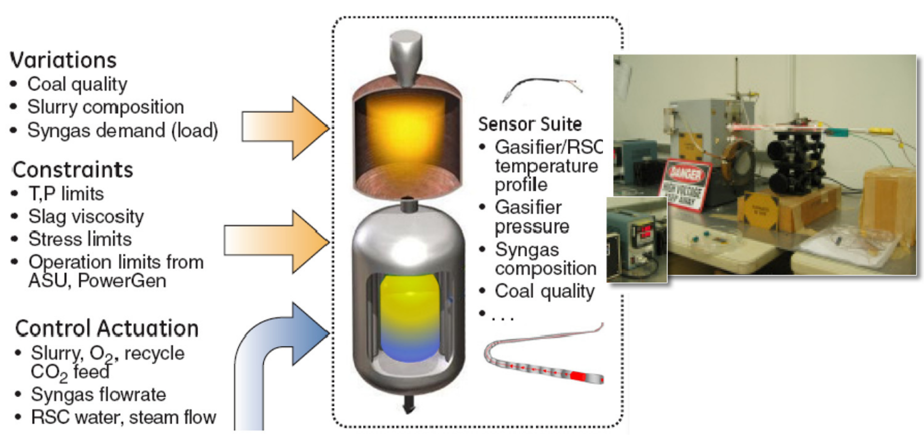
Technology Area: Advanced Process Control

Program Area: Coal Utilization Science

Gasification offers a viable pathway for the clean generation of power and fuels and a cost effective option for the sequestration of carbon dioxide. General Electric (GE) is a leader in the commercialization and deployment of gasification technology. One area of innovation is the use of advanced controls, which couples modeling and sensing to implement a set of algorithms for operating the gasifier and radiant synthesis gas (syngas) cooler; a large-scale complex system with highly integrated subsystems. Using an overall strategy of employing model-based predictive controls, GE is developing a systematic computational approach for aligning interrelated process models into a common format and model-based design of an advanced sensing and control platform solution that enables operational flexibility. For an entrained-flow gasifier and synthesis gas cooler-type system, the anticipated benefits of integrated sensing and controls are increased flexibility in operation with regard to fuel mix/type, load changes, and start-up times. The advanced sensing and controls developed for the gasification section can provide a foundation leading to other advancements in plant-level control and optimization, and also contribute to overall plant availability.

Benefits derived from this work include: (1) a process by which model developers and control system designers can employ advanced model predictive controls; (2) gasification section transient model provided by GE to National Energy Technology Laboratory (NETL) for control simulation evaluation; and (3) support for the commercialization of gasification technology employing advanced controls that enables a higher level of plant reliability and performance. GE is also documenting the challenges associated with developing the model-based controls including technology gaps and minimally acceptable time delays for On-line real-time model-based control.

The objective of this program is to develop and evaluate an advanced sensing and control solution that can enable enhanced operational flexibility of the recipients core gasification section (e.g., gasifier and syngas cooler), including flexible operation with feedstock changes, throughput changes from 50 to 100 percent to enable load following, and start-up time reduction by up to 30 percent dependent upon available actuator hardware, safety, and operability margins in the startup process.



Advanced Control Concept and Sensors used for model validation. Figure and photo provided courtesy of General Electric.

Intelligent Actuation Control Using Model-Free Adaptive Control Technology

Performer: CyboSoft, General Cybernation Group Inc.

Date: 06/30/2008 – 09/30/2011

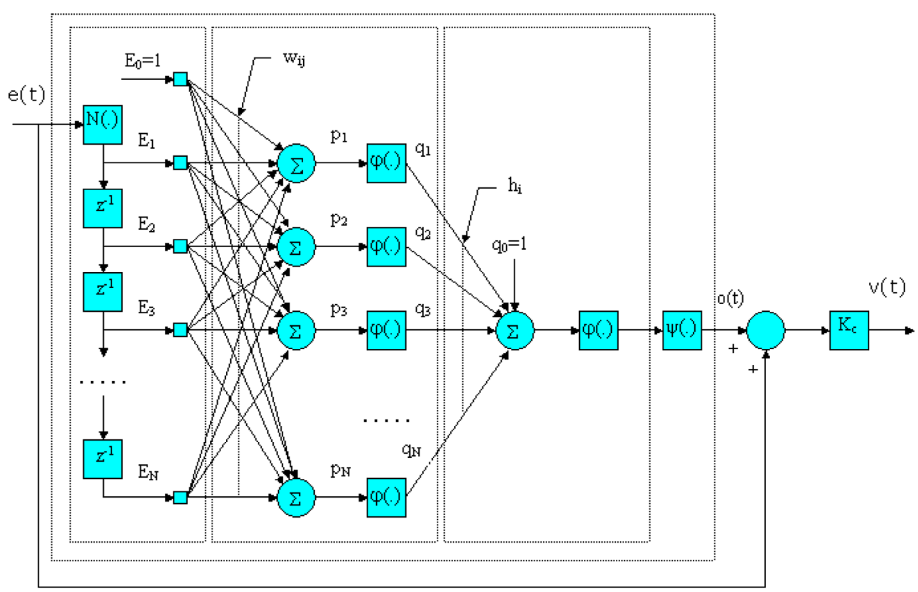
Cost: $846,480

Technology Area: Advanced Process Control

Program Area: Small Business Innovative Research

The control and optimization of coal-fired power plants depends greatly on coordinated and integrated sensing, control, and actuation technologies and products. Prior efforts to develop novel sensing and control technologies have been successful, but little work has been devoted to the coordinated control and actuation of power plants processes. Studies show as many as two-thirds of all control loop oscillations are caused by control valve or damper problems. CyboSoft, General Cybernation Group Inc.'s goal is to develop more effective and robust valve or damper position control.

Investigators will research, design, develop, test, evaluate, benchmark, and bring to production an intelligent actuation control solution to provide robust and precise control for large-scale coal-fired power plants using CyboSoft's Model-Free Adaptive (MFA) control technology. The key technical features of the solution include a control solution that is intelligent and able to adapt to significant changes in valve gain, time constant, delay time, nonlinearity, backlash, and other issues. The solution must also be able to provide more robust and precise position control and remove potential valve oscillations irrespective of the variability of valve characteristics and operating conditions. The technology will be commercialized in forms of software that can be embedded in various digital valves or damper positioned products that can be readily installed in real plants. To avoid excessive work and expenses in developing the mechanical parts, all necessary parts and components will be purchased from hardware vendors. The commercial products will be designed to be easily integrated with new and installed valves, dampers, and other actuation devices offering smooth transitions and minimal operator training and maintenance.



General outline of the MFA control approach.
Figure provided courtesy of Cybosoft General Cybernation Group.

On-Line, Real Time Coal Measurement and Data Processing to Optimize Boiler Operations

Performer: Energy Research Company and Lehigh University

Date: 06/30/2008 – 08/14/2011

Cost: $850,000

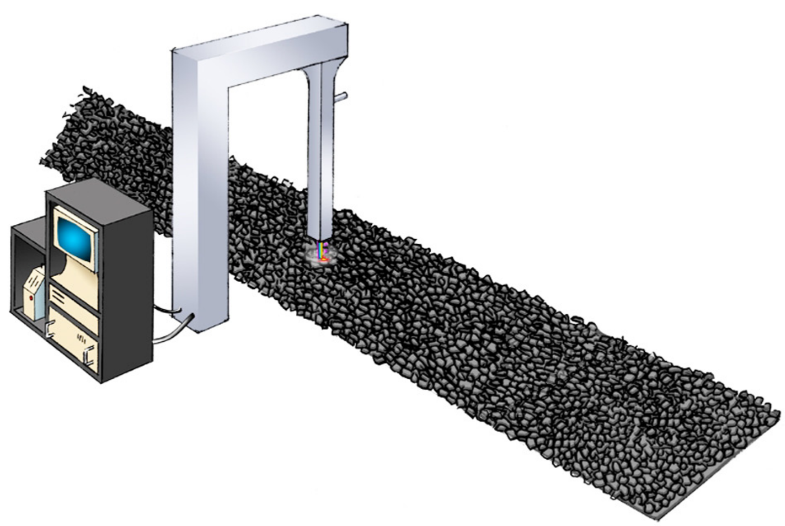
Technology Area: Advanced Process Control

Program Area: Small Business Innovative Research

Slagging and fouling of heat transfer surfaces due to ash deposition is a major concern for coal-fired electric utility boilers. The fouled tube and wall surfaces reduce heat transfer and thermal efficiency, resulting in reduced steam and combustion air temperatures, increased fuel firing rates, and increased fan power (to overcome larger pressure drops in the convective pass). Heavy slag deposits in the waterwall regions of coal-fired boilers reduces local radiation heat transfer, resulting in increased furnace exit flue gas temperatures and higher rates of thermal nitrogen oxides (NOx) formation. In addition, deposits that grow from partially blocking the spacing between tube banks to form clinkers lead to increased gas velocities and erosion, and major incidents of internal boiler damage due to fused ash material falling to the bottom of the boiler. Corrosion may also occur underneath these deposits. Overall, a reduction in boiler thermal efficiency and an increase in emissions occur, resulting in substantial revenue loss.

The team of Energy Research Company and Lehigh University are designing an On-line, *in-situ*, real-time measurement of coal properties, coupled with artificial intelligence (AI) software, to accurately predict the slagging and fouling tendencies of coal blends as they are fed into a power plant boiler.

Specifically, a system will be used to measure the coal properties in-situ and in real time. The information will be synthesized using AI software. The results will be provided to the power plant operators so they can adjust a number of parameters to mitigate slagging.



On-Line, Real Time Coal Measurement and Data Processing to Optimize Boiler Operations

Development of Self-Powered Wireless-Ready High Temperature Electrochemical Sensors of In-situ Corrosion Monitoring for Boiler Tubes in Next Generation Coal-based Power Generation Systems

Performer: West Virginia University (WVU), International Lead Zinc Research Organization, Special Metals Corp. (SMC), and Western Research Institute (WRI)

Date: 10/01/2010 – 09/30/2013

Cost: $1,175,827

Technology Area: Advanced Process Control

Program Area: Coal Utilization Science

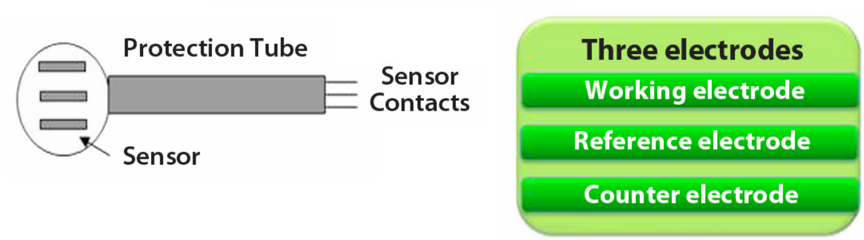
Fossil fuel power plants generate about two-thirds of the world's total electricity and are expected to continue to play an important role in the future. Increasing global energy demands, coupled with the issues of aging, inefficient power plants and increasingly strict emission requirements, will require high levels of performance, capacity, efficiency, and environmental controls from energy generation facilities. Advanced condition-monitoring networks will play an essential role in meeting these challenges by helping to enhance the overall reliability and performance of advanced fossil-energy power plants.

In this project, West Virginia University (WVU), the International Lead Zinc Research Organization, Special Metals Corporation (SMC), and Western Research Institute (WRI) have partnered to develop *in-situ* corrosion monitoring sensors for fireside corrosion of ultrasupercritical (USC) boiler tubes in next-generation pulverized coal-fired power plants. Through analysis of the currently available data, the project team believes the shortcoming of current sensors is the lack of a reliable high temperature reference electrode, which provides the reference point for all the electrochemical readings and analysis.

To address this issue, the project team will experiment with different materials for the reference electrode components, including the glass ceramic tube, electrode wire, and electrolyte solution, that are resistant to oxidation and chemical attack at high temperatures. In particular, the research team is investigating the use of beta alumina, which is considered a high quality high-temperature sodium ion conductor, for the electrode's internal wire reference electrode's membrane. Other materials being considered by the researchers include alpha alumina and other ceramics for the tube.

In-situ corrosion monitoring validation will be conducted for several key alloys with conditions closely simulating USC boiler tubes operating conditions.

The project will enhance the ability for real-time corrosion monitoring, enabling the reduction of the number of forced outages and the avoidance of unplanned events in ultra-supercritical boilers. This research will also be leveraged to other applications where corrosion in high temperature processes is a concern.



Coupled Multielectrode Sensor (CMS) Probes

Development of Standard Packaging and Integration of Sensors for On-Line Use in Harsh Environments

Performer: MesoScribe Technologies, Inc

Date: 07/01/2009 – 08/14/2012

Cost: $940,315

Technology Area: Advanced Process Control

Program Area: Small Business Innovative Research

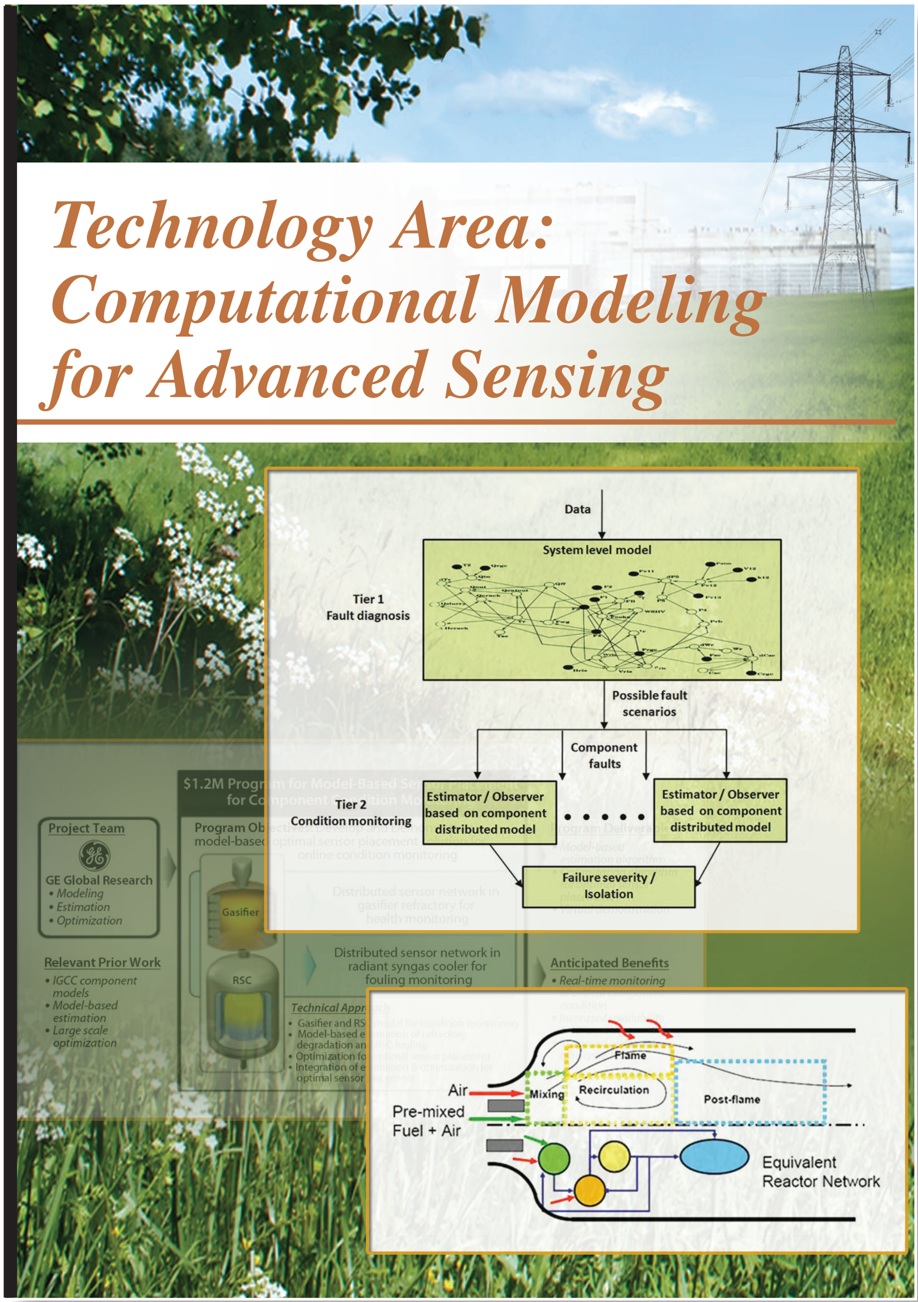
Sustainable energy initiatives focus on improving the affordability and reliability of power generation systems while eliminating harmful emissions (e.g., CO_2). Advanced process controls, which employ On-line diagnostic feedback, can drive down energy costs through performance optimizations and proactive maintenance scheduling. However, the effects of high temperatures, corrosive/oxidizing gases, and abrasive media have hindered sensor implementation within power systems. Ruggedized sensor packaging is thus needed for sensor deployment within harsh environments to enable On-line diagnostic control.

To address this need, this project will develop new sensor packaging concepts using MesoScribe's Direct Write technology, a process which deposits functional materials in three dimensions (3D) directly and conformally onto power generation components. High temperature moisture/corrosion barrier coatings will be deposited for encapsulating low-profile sensors. Durable lead-wire attachment capabilities will be developed for robust sensor routing and implementation. By leveraging Direct Write approaches for encapsulation and lead wire routing, fiber optic sensors will be integrated onto power generation hardware for advanced condition monitoring.

Direct Write is a highly versatile process well-suited for device encapsulation and robust lead connections, in turn enabling ruggedized sensor implementation. Direct Write technology offers several benefits over conventional lead wires, such as mineral-insulated metal sheathed (MIMS) type cables. Noteworthy advantages include reduced aerodynamic disruption due to the low profile nature of the deposits, improved bonding to the part, and increased repeatability and reduced labor due to the use of high-precision automation.

Direct Write Sensor Fabrication

Development of harsh environment packaging facilitates will enable the deployment of sensors for advanced power systems to improve operation efficiency, prevent unplanned shutdowns, and reduce costs and emissions. Applications areas specifically addressed include encapsulation of optical sensors for supercritical boilers, diagnostics for industrial gas turbines, and on-cell sensing for solid oxide fuel cell stacks.


Technology Area:
Computational Modeling
for Advanced Sensing
Data
System level model
Tier 1
Fault diagnosis
Possible fault
scenarios
Component
faults
Tier 2
Condition monitoring
Estimator / Observer
based on component
distributed model
Estimator / Observer
based on component
distributed model
Failure severity /
Isolation
Project Team
GE Global Research
• Modeling
• Estimation
• Optimization
Relevant Prior Work
• IGCC component models
• Model-based estimation
• Large scale optimization
Distributed sensor network in
radiant syngas cooler for
fouling monitoring
Anticipated Benefits
• Real-time monitoring
Flame
Air
Mixing
Recirculation
Post-flame
Pre-mixed
Fuel + Air
Equivalent
Reactor Network

Model Based Optimal Sensor Network for Condition Monitoring in an IGCC Plant

Performer: General Electric Global Research Center

Date: 8/20/2010 – 12/30/2012

Cost: $1,195,894

Technology Area: Computational Modeling for Advanced Sensing

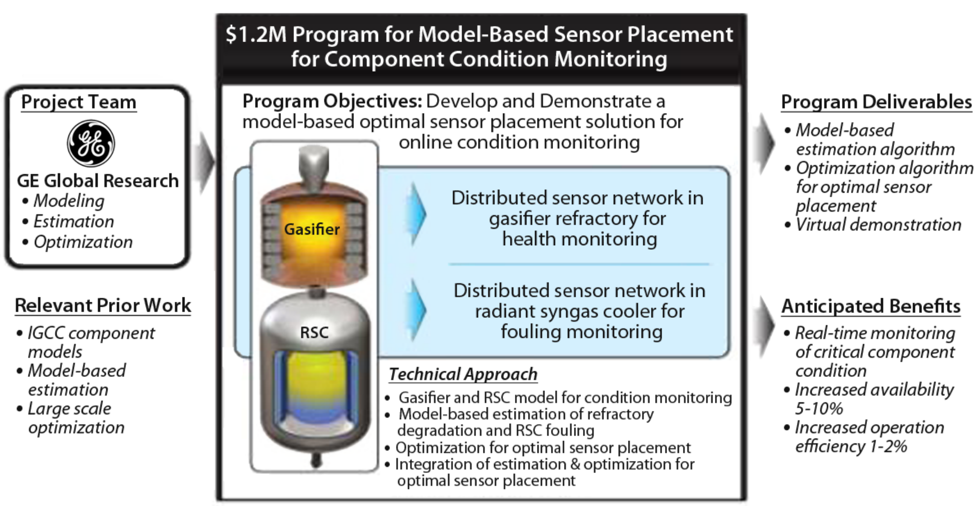
Program Area: Coal Utilization Science

Reliable and robust sensors and controls are essential to the development of high-efficiency, clean energy technologies such as low-emission power systems that use coal or other fossil fuels. Gasification offers a viable pathway for the clean generation of power and fuels and a cost effective option for the sequestration of carbon dioxide. General Electric (GE) Global Research is developing advanced model-based sensing and controls technology for the gasification section in an Integrated Gasification Combined Cycle (IGCC) plant to attain enhanced robustness, efficiency, and operational flexibility through increased computationally based automation.

The gasification section within an IGCC plant is an area where innovative approaches using computational techniques can improve the operation and overall condition monitoring of the components. Modeling techniques based on first principles can be used to identify plausible solutions for improving operation and control of the gasification section where traditional heuristic techniques have proven to be limited.

With an overall strategy of employing first-principles model-based analysis, GE Global Research will extend their models for the gasification section, to implement a nonlinear estimation algorithm to monitor the condition and extent of degradation in gasifier refractory and fouling in the syngas cooler, and to perform optimization for optimal sensor placement (OSP) to achieve monitoring requirements. The performance of the OSP algorithm and resulting monitoring solution will be demonstrated using representative test cases. When completed, the approach will be applicable to other systems for placing sensors to enable the creation of condition monitoring sensor networks.

When implemented, optimal sensor placement will enable more accurate assessment of the components' condition and will lead to operations that support higher reliability, availability and potential increases in plant efficiency.



Program Overview for Model-Based Sensor Placement for Component Condition Monitoring

Package Equivalent Reactor Networks as Reduced Order Models for Use with CAPE-Open Compliant Simulations

Performer: Reaction Design

Date: 10/1/2009 – 9/30/2012

Cost: $1,045,838

Technology Area: Computational Modeling for Advanced Sensing

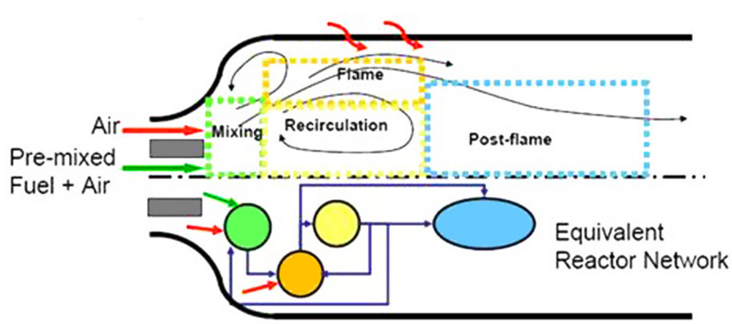
Program Area: Coal Utilization Science

Using high-fidelity fluid-dynamics models as input, Reaction Design will extend existing technology that is designed to automatically extract equivalent reactor networks (ERNs) from the computational fluid dynamics (CFD) simulation. The extraction is based on certain criteria for grouping regions of similar kinetic behavior. The ERNs are composed of idealized reactors (e.g., perfectly stirred and/or plug-flow reactors) that interact through mass-flow and heat-transfer connections to represent the complex flow. In contrast to the CFD simulations, however, the ERNs allow inclusion of detailed kinetics representations of the reacting-flow process, including particle-gas interactions, gas combustion, and emissions production.

A key component of this project is to encapsulate the CHEMKIN™-based ERN models as CAPE-OPEN-compliant objects that can be used in general flow-sheet simulation software. By combining existing detailed-kinetics reactor-network capability from CHEMKIN-PRO (Reaction Design) with CAPE-OPEN interface standards (CAPE-OPEN Laboratories Network), state-of-the-art kinetics modeling will be enabled within flow-sheet type simulations. This will be the basis for developing accurate reduced-order models for gasification/combustor processes.

This effort will involve sequential steps to build and test the new capability in order to achieve validated component models. Industry guidance will provide important design parameters for gasifiers as well as validation data to test resulting models.

The goal of this project is to enable an advanced form of reduced-order modeling for representation of key unit operations in flow-sheet simulations. Using high-fidelity fluid-dynamics models as input, the existing technology for the automatic extraction of ERNs from the CFD solution will be extended. While the technology has already been established for gas-turbine combustors, the aim of this project will be to extend the methodology to gasifiers.



Package Equivalent Reactor Networks as Reduced Order Models

Model-Based Sensor Placement for Component Condition Monitoring and Fault Diagnosis in Fossil Energy Systems

Performer: Texas Tech University and West Virginia University

Date: 01/01/2001 – 12/31/2013

Cost: $981,813

Technology Area: Computational Modeling for Advanced Sensing

Program Area: Coal Utilization Science

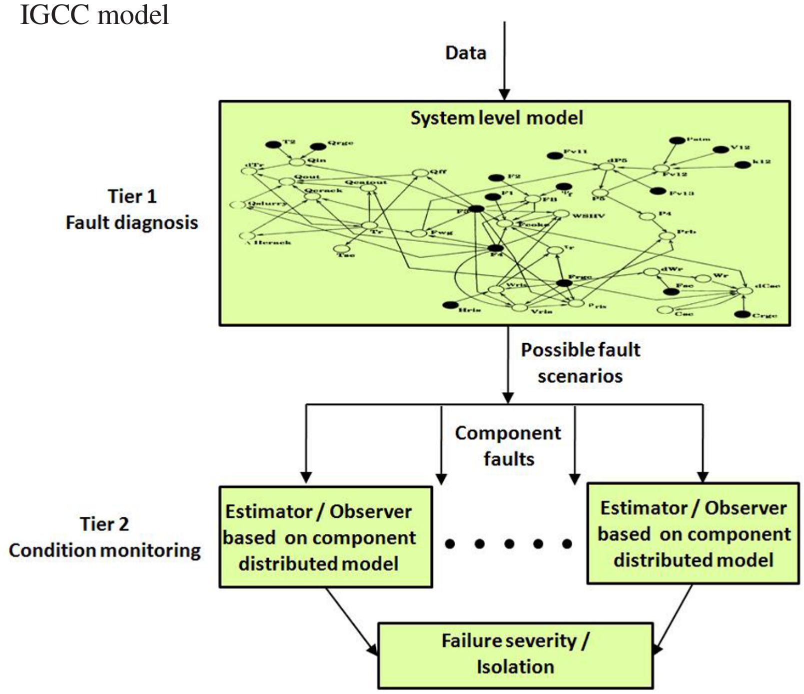
Fossil fuel power plants generate about two-thirds of the world's total electricity and are expected to continue to play an important role in the future. Increasing global energy demands, coupled with the issues of aging, inefficient power plants, and increasingly strict emission requirements, will require high levels of performance, capacity, efficiency, and environmental controls from energy generation facilities. Advanced condition-monitoring networks will play an essential role in enabling power plants to meet these challenges by enhancing the overall reliability, performance optimization, and availability of emerging near-zero emissions power production systems.

In this project, Texas Tech University (TTU) and West Virginia University (WVU) will develop model-based sensor placement algorithms for maximizing the robustness and effectiveness of the sensor network to monitor the plant health both at the unit level and at the systems level. This will be achieved by developing a two-tier sensor network algorithm capable of performing component condition monitoring and system-level fault diagnosis. The algorithms will be implemented on a plant-wide simulation of a coal-based Integrated Gasification Combined Cycle (IGCC) plant with a rigorous gasifier model.

To meet the objective, a comprehensive list of faults in a typical IGCC plant will be identified. For critical processes such as the gasifier, more detailed failure modes will be considered. Structural changes to the Aspen Dynamics™ (Aspen Technology, Inc.) model will be performed to incorporate simulation models for the identified faults.

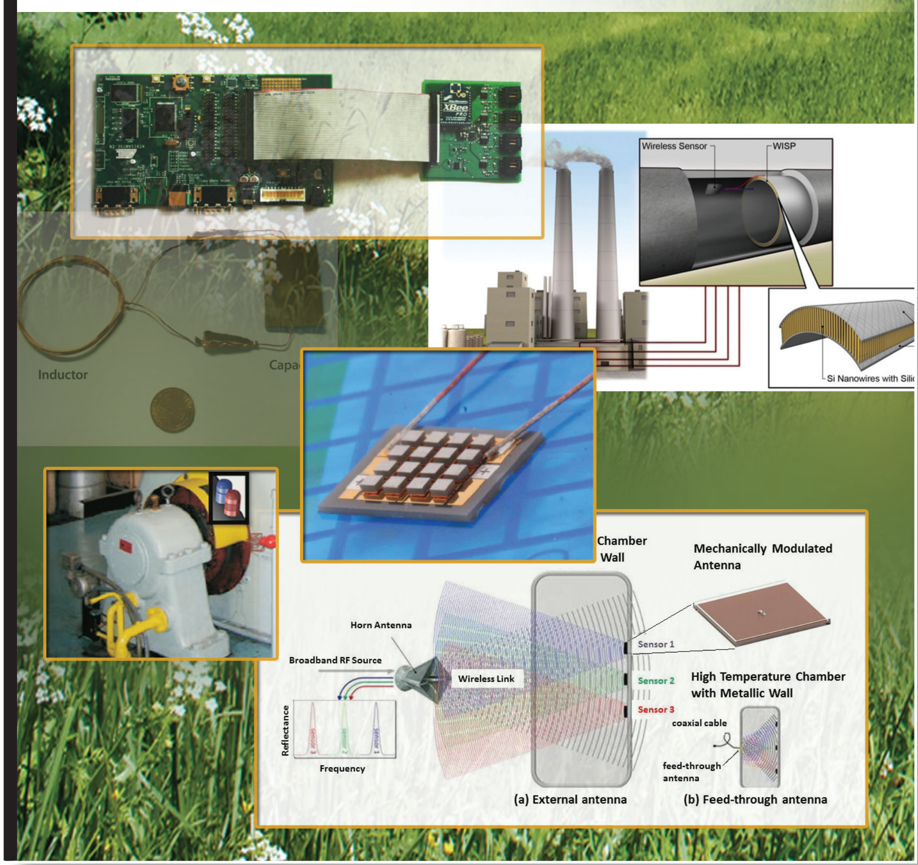
Sensor placement algorithms for condition monitoring and fault diagnosis will be developed and tested on the plant-wide dynamic IGCC model

The result of this project will be model-based sensor placement algorithms that will increase the efficiency and effectiveness of fossil energy systems sensor networks. More specifically, the sensors will monitor the status of equipment, materials degradation, and process conditions that impact the overall health of a component or system in the harsh high-temperature, highly corrosive environments of advanced power plants.



Model-Based Sensor Placement Algorithms

Technology Area: Sensor, Wireless Communications, Energy Harvesting Integration



A Novel Wireless Sensor Network with Advanced Prognostic Algorithms for Condition-Based Maintenance of Critical Power Plant Components

Performer: Signal Processing, Inc., University of Texas at Arlington, and General Electric

Date: 04/23/2007 – 01/14/2011

Cost: $850,000

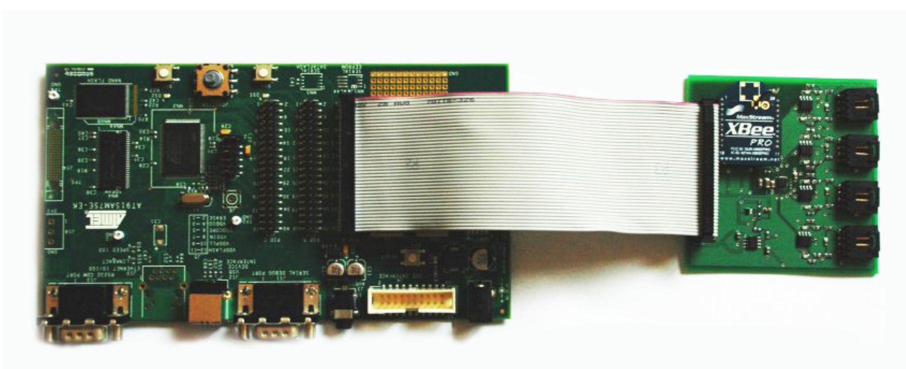
Technology Area: Sensor, Wireless Communications, Energy Harvesting Integration

Program Area: Small Business Innovative Research

Improving efficiency, reducing emissions, and reducing costs are key objectives for power plants. The achievement of these objectives requires the development of two mutually dependent functions: distributed data acquisition and real-time data interpretation. Signal Processing, Inc., University of Texas at Arlington, and General Electric will combine a wireless sensor network (WSN) with an advanced diagnostic and prognostic capability to monitor and assess critical power plant components. First, the hardware system consists of a WSN with appropriate sensors and data acquisition card, and a portable personal computer (PC). The portable PC has advanced prognostic algorithms and user-friendly Graphical User Interface for displaying component health status and trends. Second, the prognostics software has an innovative tool based on a Hidden Markov Model (HMM). The HMM has been very successful in capturing the transitions between various degraded states. The WSN combines low-cost hardware and innovative prognostic software in a unified framework and can subsequently reduce the system downtime and maintenance costs.

In Phase I, two testbeds were constructed: one for emulating electrical faults and one for emulating mechanical faults. Real-time experiments were performed, with wireless data collection used in all experiments. Real-time health monitoring algorithms were developed, and actual bearing data were used to validate the algorithms. Phase II implements all of the diagnostic and prognostics tools in a real-time processing unit. Real-time field tests are being carried out with a WSN to collect various sensor data.

The efficiency of power systems are closely connected to the proper operation of some critical components. For example, a faulty pressure sensor may feed incorrect pressure information to the system controller, which then generates the wrong control commands and causes less than optimal power generation. Consequently, system efficiency decreases. Fault diagnostics and prognostic algorithms can reveal component faults in the incipient stage. Similarly, emissions are closely related to efficiency of operations, and early detection of component faults can help improve the efficiency of the power generators and reduce the harmful emissions. In addition, minimizing downtime can significantly reduce operating costs.



Custom-made wireless-sensor-network remote sensing unit. Photo provided courtesy of Signal Processing Inc.

Ultra-High Temperature Distributed Wireless Sensors

Performer: Prime Photonics, LC and Virginia Polytechnic Institute and State University

Date: 10/01/2009 – 09/30/2012

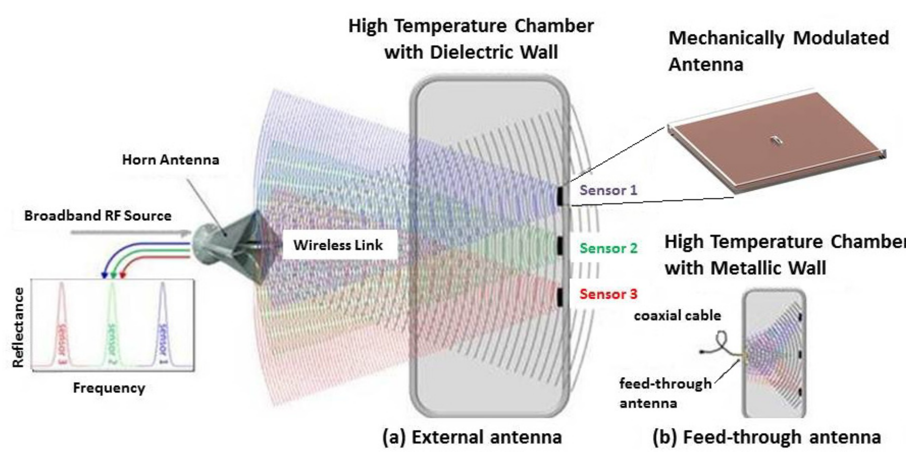
Cost: $810,954

Technology Area: Sensor, Wireless Communications, Energy Harvesting Integration

Program Area: Coal Utilization Science

Prime Photonics, LC and the Virginia Tech Antenna Group are developing a wireless sensor technology capable of operating at very high temperatures in highly corrosive environments. The technology completely eliminates the need for cables connecting to the sensors. In many cases, it can avoid the need to machine feed-through to gain access into plant interiors. The technology is enabled by recent developments in radio frequency identification (RFID), high-temperature materials, and mechanically modulated antennas.

The goal of this project is to develop and demonstrate a robust and accurate wireless sensing technology for use at extreme temperatures in highly corrosive environments. The project is divided into two phases. The goal of Phase I is to better understand the radio frequency environment where the system will operate, as well as the electromagnetic properties of the materials to be used. Researchers will identify frequency bands where wireless sensing is feasible and perhaps discover additional mechanisms for sensing the environment. The team will create the detailed design of the wireless sensors. The goal of Phase II is to perform the testing of the wireless sensors and their packaging. A number of prototype designs can be tested at low temperature to identify an optimum electromagnetic design. An interrogation system will be designed based on the knowledge gained during the project. The team will complete the sensor design and perform testing in a realistic environment.



Novel wireless sensors using radio frequency identification will allow measurement of temperature and pressure in harsh high-temperature environments. Figure provided courtesy of Prime Photonics, LC.

Battery-Free Wireless Sensor Network for Advanced Fossil-Fuel-Based Power Generation

Performer: University of Puerto Rico Mayaguez

Dates: 03/01/2007 – 02/28/2011

Cost: $192,782

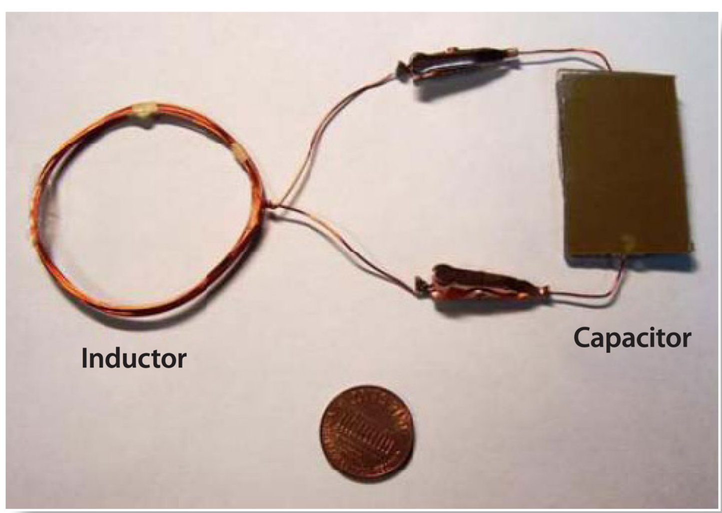
Technology Area: Sensor, Wireless Communications, Energy Harvesting Integration

Program Area: Historically Black Colleges and Universities (and Other Minority Institutions)

This project addresses advanced fossil-fuel-based power industry needs for the development of innovative sensor technology in high-temperature harsh environments. The research is extending passive wireless-telemetry sensor technologies developed at the University of Puerto Rico to physical and chemical sensing applications for intelligent control of advanced fossil-fuel-based power generation system. High-temperature sensing materials with dielectric response to physical and chemical exposure are being developed and characterized. The researchers will investigate a battery-free wireless sensing mechanism to develop novel wireless sensors and sensor network for physical and chemical parameters monitoring in a harsh environment.

Multilayer Ceramic Integrated Circuit (MCIC) technology and ceramic Green Tape™ material system are being incorporated with capacitive sensing materials to ensure sensors operation in harsh environments at temperatures up to 800 °C. The measured parameter is frequency encoded and wirelessly monitored by a receiver. Energy for the sensor operation is also fed wirelessly. Thus, no wires or batteries are attached to the sensor unit. The researchers are also adopting the hybrid Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) protocol to build a wireless sensor network and develop associated multi-coils swept frequency reader. This frequency tracking method will make the system more robust to noise.

This project extends the knowledge base of passive wireless sensing technologies in harsh environments by demonstrating a novel, battery-free, wireless sensing platform and wireless sensor network. Since the sensor is being fabricated using MCIC technology, the sensor built with planar multilayer thick-film structure has small size, light weight, low power consumption, and very low cost. It can easily fit on the surface of any component to be monitored at less than one millimeter in height and less than ten grams in weight.



Sensor prototype of passive wireless temperature sensor for harsh environment (left) and High temperature sensing element (right). Photos provided courtesy of University of Puerto Rico Mayaguez.

Energy-Harvester-Powered Wireless Sensors for Extreme Temperature Environments

Performer: KCF Technologies, Inc.
Date: 06/01/2010 – 12/01/2010

Cost: $100,000

Technology Area: Sensor, Wireless Communications, Energy Harvesting Integration

Program Area: Small Business Innovative Research

In the past decade, wireless sensor development has primarily focused on consumer and commercial markets. Industrial wireless sensors offer a similarly high value in terms of increased process and equipment monitoring at significantly lower cost than hardwired sensors. These benefits are being further enhanced by improvements in equipment diagnostic and prognostic analysis. Application of wireless sensors in industrial markets is generally more technically challenging due to the need for a higher level of robustness and tolerance to harsh environmental conditions. Although numerous wireless sensor products exist for industrial wireless sensing, powering the sensors and using them in high-temperature environments remain key technical limiters for broad industrial market applicability.

KCF Technologies, Inc. will develop energy-harvester-powered sensors for high-temperature environments. The project will addressing current technology limitations by focusing on (1) temperature control of electronics in high-temperature environments, (2) high-temperature tolerance of thermal and vibration energy harvesters, (3) conditioning and reliably supplying voltage to wireless sensors, and (4) energy-harvester mechanical robustness.

The high-temperature wireless solution will provide a finished platform for interfacing existing high-temperature sensors. The sensor system would function as a replacement for an existing sensor systems. The high-temperature system will also have new functionality for measuring vibration to perform equipment diagnostics and prognostics. KCF's existing vibration diagnostic software will be coupled with the new measurement system. Harvesting energy to power these wireless sensors can reduce total lifecycle costs by eliminating the need for a battery change. The benefits of these technologies are further enhanced by insertion into high-temperature environments.

Energy-harvester- powered high-temperature wireless sensors.
Photo provided courtesy of KCF Technologies, Inc.

Self-Powered Wireless Sensor System for Power Generation Applications

Performer: Wireless Sensor Technologies, LLC

Date: 06/01/2010 – 02/01/2011

Cost: $100,000

Technology Area: Sensor, Wireless Communications, Energy Harvesting Integration

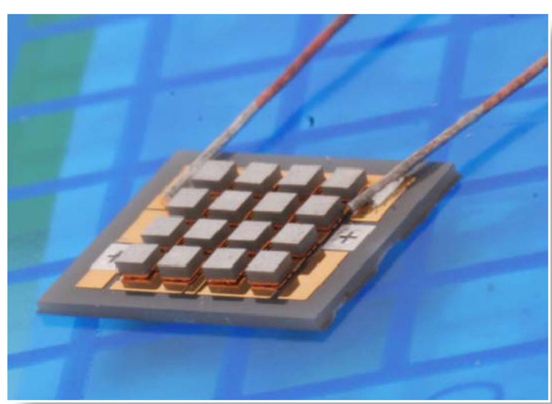
Program Area: Small Business Innovative Research

Researchers at Wireless Sensor Technologies are developing and demonstrating a high reliability waste heat-enabled power supply and wireless sensor system for power generation applications. This system enables the addition or expansion of condition-based maintenance (CBM) in power generation plants. Condition-based maintenance systems significantly improve the effectiveness of maintenance programs for complex systems by optimizing the timing and focus of the procedure. The approach minimizes the associated maintenance costs, and the wireless sensor system enables CBM sensors to be easily added to existing plants and equipment.

This system includes a unique power supply that utilizes waste heat from the plant equipment. Also provided are pressure and temperature sensors that may be used in the hot sections of turbine engines and mounted on rotating components. The system eliminates most system interconnects through its wireless networked architecture of individual sensor nodes. The system and its individual temperature and pressure sensors are being effectively utilized in the development phases of power plant equipment such as gas and steam turbines.

The project scope is to develop a self-powered wireless sensor system for power generation applications that is operated using a semiconductor thermo-electric generator (TEG)-based power supply. This supply can provide continuous reliable power to the sensor system. The sensors communicate between sensor nodes via a wireless mesh network that is flexible, self-healing, and uses existing commercial protocols.

The wireless network enables the addition of sensors around the plant without the need to add cables for input or output signaling. Capabilities include temperature and pressure sensors to be operated at temperatures up to and exceeding 1000 °C; passive wireless thin-film temperature sensors to measure the surface temperature of the thermal-barrier-coated (TBC) turbine blades in the hot section of a gas turbine engine-based generator; and passive wireless heat-flux sensor to monitor the integrity the TBC coating of the turbine blade or other areas where temperatures exceed 1200 °C.



Individual thermoelectric generation module.
Photo provided courtesy of Nextreme Thermal Solutions, Inc.

Wireless Seebeck Power

Performer: Physical Optics Corporation

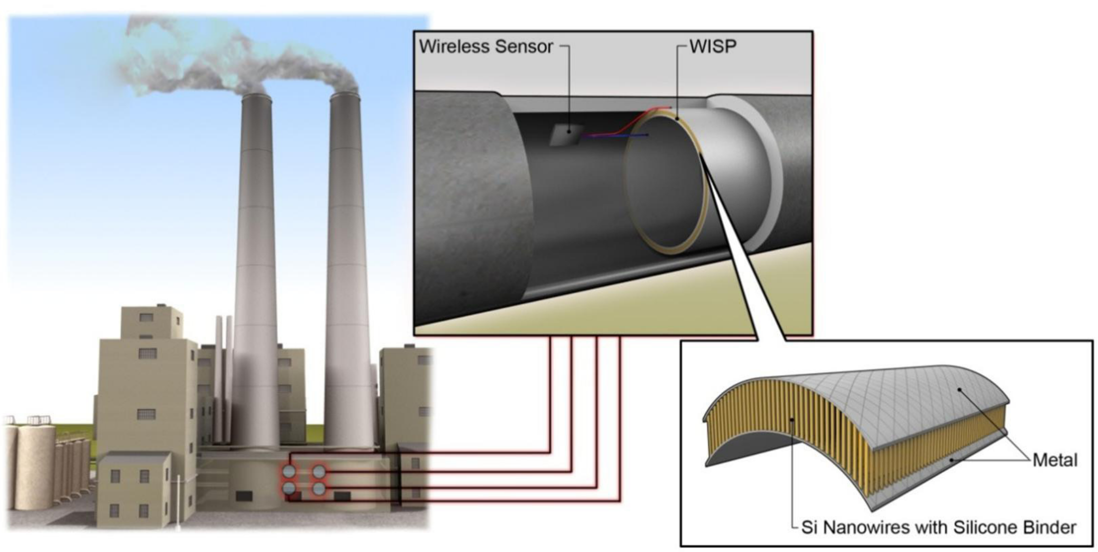
Date: 07/01/2010 – 03/31/2011

Cost: $99,997

Technology Area: Sensor, Wireless Communications, Energy Harvesting Integration

Program Area: Small Business Innovative Research

Power plants lose large amounts of energy from vibration and heat. Developing technology that can collect this energy will allow wireless sensors to operate without periodic battery replacement or connection to a primary power grid. A complex array of wireless sensors used to monitor power plant performance requires a continuous power source. Self-powered sensors will be able to collect energy from the ambient environment, as opposed to having power supplied with batteries that frequently need replacement or from an expensive centralized power grid. Physical Optics Corporation is developing a new class of thermoelectric nanodevices that can efficiently convert thermal energy into electrical power. They will be able to provide low-cost energy due to the low material cost coupled with simple manufacturability applied to a large number of units. Power supply for these units will be reliable because of the constant thermal gradient within power plants. These devices allow for the development of more efficient and low-cost power scavenging technology that can provide a new means to design and implement wireless sensor systems. In addition, this technology could be developed and expanded to collect the energy from engines to improve power generation efficiency by collecting thermal energy that is normally lost to the environment.



Wireless Seebeck Power used as a power harvester to power wireless sensors in power plants. Figure provided courtesy of Physical Optics Corporation.

Galfenol Energy Harvester for Wireless Sensors

Performer: Techno-Sciences, Inc. and University of Maryland

Date: 06/01/2010 – 03/31/2011

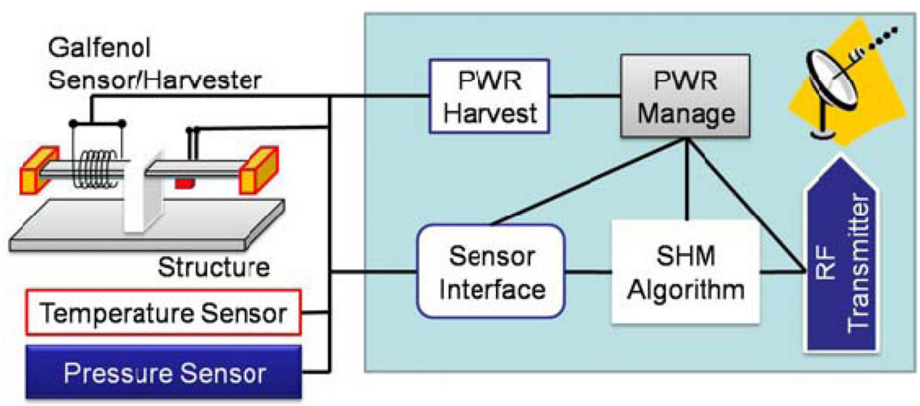
Cost: $ 99,915

Technology Area: Sensor, Wireless Communications, Energy Harvesting Integration

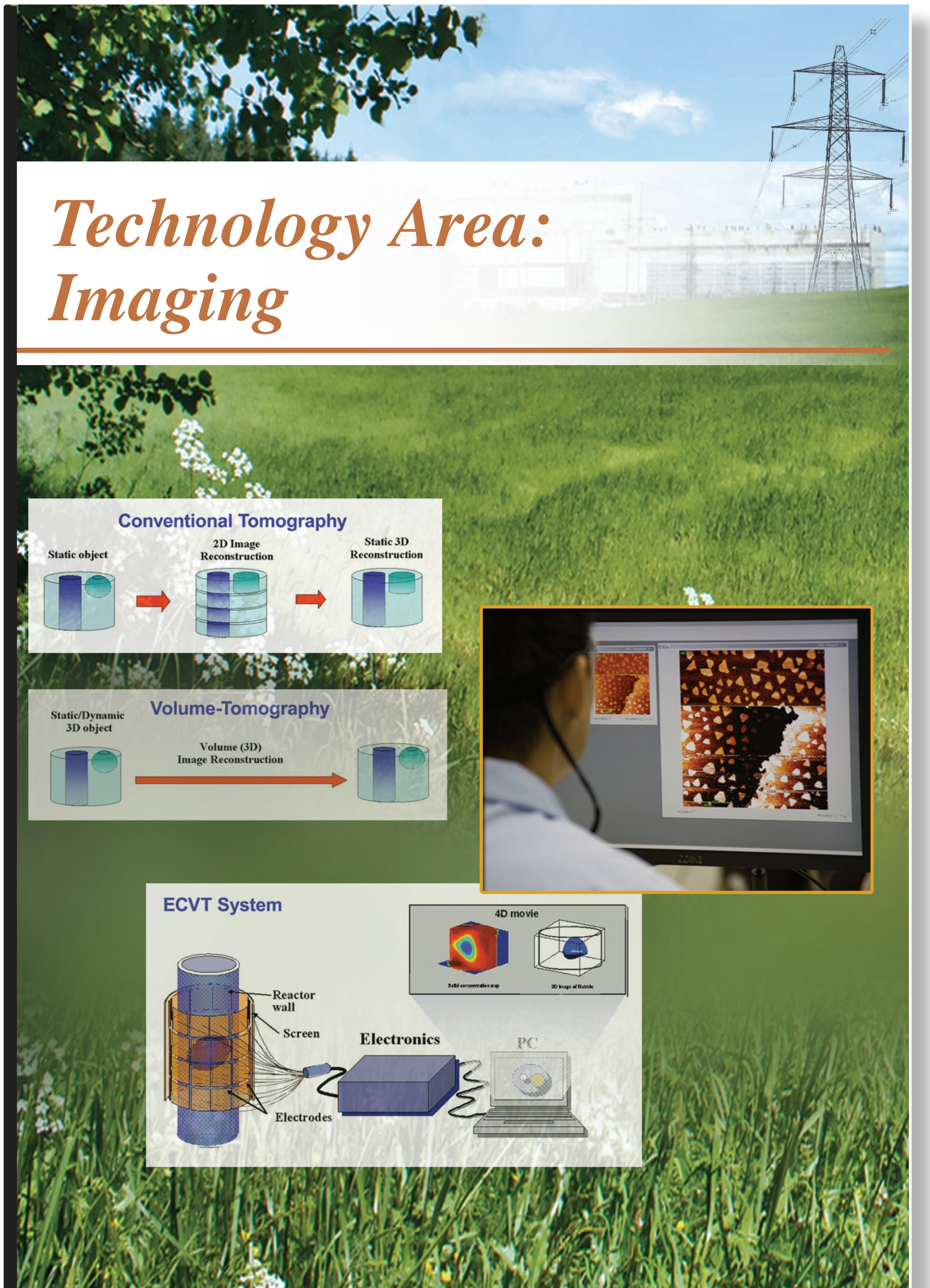
Program Area: Small Business Innovative Research

Advanced power generation facilities benefit from the ability to track operational parameters as a means of increasing efficiency and diagnosing faults. A deployed system of temperature sensors, pressure sensors, and chemical composition analyzers distributed throughout a facility coupled with wireless communication technologies may provide a method for On-line tracking of performance. Techno-Sciences, Inc. and University of Maryland will investigate the use of an innovative energy harvester device to provide long-term power suitable for wireless sensor networks using advanced materials to convert readily available vibration energy into useful electrical energy. The benefit of such an approach is the ability to retro-fit a wireless sensor system which allows for real-time monitoring of power plant processes without introducing significant integration related issues. An added benefit is the ability to reconfigure the wireless system as desired. A wireless sensor with an appropriately- sized power source would allow for rapid upgrade of existing power generation facilities to improve efficiency and aide in maintenance efforts. The device is based on an innovative use of the magnetostrictive effect, which has been demonstrated in the laboratory environment and has the potential to outperform devices using the conventional piezoelectric approach.

Researchers will develop and design the device for use with an appropriate wireless-sensor configuration to demonstrate the ability of the innovative energy-harvesting device to power a wireless sensor. In addition to increasing the efficiency of power plants, such devices may be applicable in monitoring the structural health of buildings and bridges, and monitoring naval vessels. The device is being designed to be robust with an ability to be tailored for a specific operation environment.



Schematic illustrating the features of the sensor node with integrated Galfenol-based energy harvester. Photo provided courtesy of Techno-Sciences, Inc.


Technology Area:
Imaging
Conventional Tomography
Static object
2D Image
Reconstruction
Static 3D
Reconstruction
Volume-Tomography
Static/Dynamic
3D object
Volume (3D)
Image Reconstruction
ECVT System
4D movie
Reactor
wall
Screen
Electronics
PC
Electrodes

Development and Implementation of 3-D, High-Speed Capacitance Tomography for Imaging Large-Scale, Cold-Flow Circulating Fluidized Bed

Performer: Tech4Imaging and Ohio State University

Date: 10/01/2008 – 09/30/2011

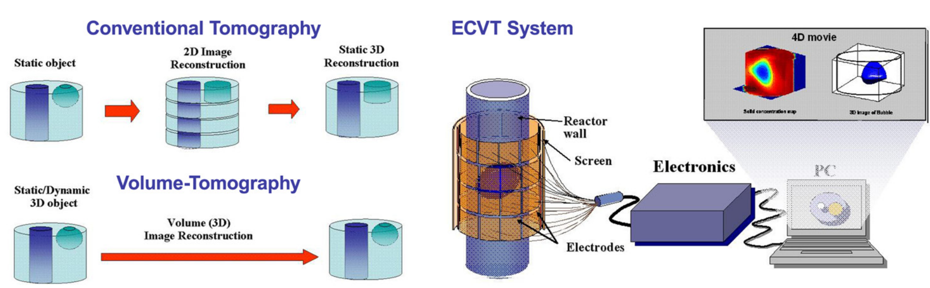
Cost: $1,167,050

Technology Area: Imaging

Program Area: Coal Utilization Science

The inherently complex nature of multiphase flows such as those encountered in fluidized beds requires a multi-dimensional measurement technique capable of providing real-time monitoring of the process dynamics and physical properties. Tech4Imaging and Ohio State University will develop and demonstrate a three-dimensional (3-D) high-speed electrical capacitance volume tomography (ECVT) system. The ECVT uses capacitance measuring equipment and high-level computing to render 3-D images directly from the measured capacitance data of multiphase flow systems. Conventional electrical capacitance tomography (ECT) provides 2-D images of flow by averaging a phase concentration over the capacitance sensor length. For proper understanding of flow behavior, 3-D volume images that depict different phases' concentrations are required. Acquiring 3-D images requires distribution of the sensors in three dimensions. In ECVT, changes in the sensor shape and distribution of sensor plates provide 3-D characteristics so that 3-D imaging can be obtained despite the limitation on capacitance sensor size. In the past, this approach led to a highly non-linear image reconstruction problem that was difficult to solve. Tech4Imaging has developed software implementing a reconstruction technique capable of providing a solution.

The goal of the project is to develop a 3-D, high-speed capacitance tomography system to image large-scale, cold-flow circulating fluidized beds (CFB). The overall objective of the project is to develop and adapt an ECVT system to image multiphase flows common to CFB and evaluate its ability to collect data useful for validating multiphase flow models. The specific objectives of the project include developing high-speed capacitance acquisition hardware with up to 50 imaging frames per second; developing 3-D reconstruction software; designing custom 3-D capacitance sensors for the CFB; conducting a thorough analysis of acquired images; and installing the capacitance sensors and delivering a fully operational ECVT system. Multiphase flows are commonly encountered in industrial operations such as fluidized-bed combustors, coal gasifiers, carbon capture processes, and Fischer-Tropsch synthesis. A dedicated 3-D ECVT for imaging fluidized-bed systems can enable a less expensive exploration of options that may improve the processes involved in producing power using cold-flow circulating fluidized beds. This optimization of power production processes can lead to more efficient uses of domestic fuel sources with lower emissions in order to support DOE's energy security mission.



Conventional tomography constructs a 3D image by stacking 2D images averaged along the length of the 2D capacitance sensor (top left), whereas volume tomography produces a 3D image directly from the 3D capacitance sensor and avoiding stacking (bottom left). Block diagram of an ECVT system (right). Figures provided courtesy of Tech4Imaging.

List of Figures

OPTICAL SENSING

MICROSENSORS

ADVANCED PROCESS CONTROL

COMPUTATIONAL MODELING FOR ADVANCED SENSING

SENSOR, WIRELESS COMMUNICATIONS, ENERGY HARVESTING INTEGRATION

IMAGING

Glossary/Acronyms

AFM	Atomic Force Microscopy
AI	Artificial Intelligience
AR	Advanced Research
CBM	Condition Based Maintenance
CCS	Carbon Capture and Storage
CFB	Circulating Fluidized Bed
CFD	Computational Fluid Dynamics
CL	Chemical Looping
CPT	Virginia Tech Center for Photonics Technology
CUS	Coal Utilization Science
DOE	Department of Energy
ECT	Electrical Capacitance Tomography
ECVT	Electrical Capacitance Volume Tomography
EDS	Energy Dispersive X-Ray Spectrometry
ERN	Equivalent Reactor Network
FDMA	Frequency Division Multiple Access
FOCS	Fiber Optic Chemical Sensors
FT-IR	Fourier Transform Infrared Absorption
GE	General Electric
GUI	Graphical User Interface
GTI	Gas Technology Institute
HBCU	Historically Black Colleges and Universities
HEIFPI	Hybrid Extrinsic/Intrinsic Fabry-Perot Interferometer
HMM	Hidden Markov Model
ICOS	Integrated Cavity Output Spectroscopy
IFPI	Intrinsic Fabry-Perot Interferometer
IGCC	Integrated Gasification Combined-Cycle
LBCO	$LnBaCo_2O_{5+d}$
LGR	Los Gatos Research
LLC	Limited Liability Company
LPFG	Long Period Fiber Grating

MCIC	Multilayer Ceramic Integrated Circuit
MEMS	Micro Electro Mechanical Systems
MFA	Model-Free Adaptive
MIMS	Mineral-Insulated Metal Sheathed
MTBA	Mean Time Between Attentions
NETL	National Energy Technology Laboratory
OSP	Optimal Sensor Placement
PID	Proportional Integrated Derivative
PRLC	Prime Research, LC
R&D	Research and Development
RFID	Radio Frequency Identification
RUL	Remaining Useful Life
SBIR	Small Business Innovative Research
SC	Supercritical
SiC	Silicon Carbide
SEM	Scanning Electron Microscopy
SMS	Single-Mode-Multimode-Single-Mode
TBC	Thermal Barrier Coated
TDL	Tunable Diode Laser
TDMA	Time Division Multiple Access
TEG	Thermo-Electro Generator
TLPFG	Thermal Long Period Fiber Grating
UCR	University Coal Research
UIUC	University of Illinois Urbana-Champaign
USC	Ultra Supercritical
VT	Virginia Polytechnic Institute and State University
VTAG	Virginia Tech Antenna Group
WSN	Wireless Sensor Network
XRD	X-Ray Diffraction
XPS	X-Ray Photoelectron Spectroscopy

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http://www.netl.doe.gov/technologies/coalpower/advresearch/

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